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Catalytic decomposition of nitrous oxide for spacecraft propulsion applications. (Phase 1)

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PROJECT

NITROUS OXIDE CATALYTIC DECOMPOSITION

REVISION

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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Surrey Satellite Technology, Ltd. as follows: Work package 1 (2 months - $10 K)
A paper study will be undertaken to compare nitrous oxide mono-propellant thrusters with hydrogen peroxide and hydrazine mono-propellant thrusters. A test plan for the nitrous oxide mono-propellant thrusters experimental work will also be produced.
Work package 2 (10 months - $40 K)
From the experimental data an operational envelope for each catalyst will be defined. Once the main parameters are known, an analytical simulation will be performed to minimise heat losses from the system. Nitrous oxide injection into the chamber will be optimised. Improvements to the thruster's design will be suggested to enhance performance. A final report will also be produced. The final report will describe the apparatus, test set-up and measurement techniques used for testing, contain the recorded values of pressures, temperatures, nitrous oxide mass flow rates, and discuss the results obtained. A proposal for further development and design of the nitrous oxide thruster will be presented.

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1. INTRODUCTION

This report summarises the results of nitrous oxide catalytic decomposition research performed by Surrey Satellite Technology Ltd. (SSTL) for European Office of Aerospace Research and Development (EOARD) under contract #994100.
The research was performed between September 1999 and September 2000.

2. PURPOSE AND OBJECTIVES

The main purpose of the research is to develop new technology for small spacecraft propulsion using nitrous oxide as a propellant. Such a technology should provide higher total spacecraft velocity change performance compared to traditional cold-gas propulsion systems used on small satellites.
The objectives of this phase of the research were to:

- Prove the feasibility of the suggested concept of nitrous oxide catalytic decomposition for space propulsion.
- Obtain basic experience regarding nitrous oxide catalytic and self-sustaining decomposition to develop experimental monopropellant thrusters.
- Based on the experience generate a proposal for further research in the area leading to the development of flight thruster.

3. WORK SCOPE

The *Phase 1* research work comprised three packages:
1. Study
2. Testing
3. Analysis

4. STUDY RESULTS

Theoretical study of expected performance of nitrous oxide propulsion is extended from originally proposed study of monopropellant thrusters to the study covering performance on nitrous oxide propulsion in general.
Reasons for investigation of nitrous oxide as a rocket propellant, main properties of this gas, and its space related applications are listed in the background section. The background section also covers the issues related to nitrous oxide storage and decomposition. Based on performance comparison of nitrous oxide to conventional and alternative propulsion, the multi-mode propulsion system using this gas is introduced.

4.1 Background

The small satellite industry depends on secondary launch opportunities. The limited number of such opportunities restricts the variety of satellite orbits. Therefore, for a spacecraft to continue to exploit

the availability of launches and expand its capability for more ambitious communications, remote sensing and science missions, a propulsion system is required.

There are three main propulsion system functions for satellites:

- Attitude Control - keeping a spacecraft pointed to the desired direction.
- Orbit Maintenance (station-keeping) - keeping a spacecraft in the desired mission orbit.
- Orbit Manoeuvring - moving a space vehicle to another desired orbit.

On larger spacecrafts (>500kg), these needs have been traditionally satisfied by the following system options:

- Cold-gas propulsion – mainly using nitrogen for attitude control
- Hydrazine-based systems – for attitude control, station-keeping and orbit manoeuvring
- Solid rockets – for orbit manoeuvring

However, scaling a satellite down imposes unique integration requirements and constraints for propulsion systems. For example,

- Low specific impulse performance of cold-gas propulsion (typically 60s) aggravated by severe volume constraints (propulsion envelope volume of about 7 litres), limits the range of typical (<75kg) micro-satellite orbital transfer manoeuvres to approximately 5m/s.
- Hydrazine-based systems rely on highly toxic propellant. This demands elaborate system development and pre-flight safety requirements. To reduce mission life-cycle costs, spacecraft manufacturers would prefer to reduce or eliminate this expense, which can be prohibitive for small, university-based missions.
- Solid rocket motors have similar expensive requirements for safety and handling, which also increase their life-cycle costs. In addition, the "single-shot" nature of solids makes them unsuitable for multi-thrust mission requirements.
- The high power demands (>100W) of "off-the-shelf" electrostatic and electromagnetic propulsion systems cannot be met by micro-satellite power systems delivering <50W (orbit average). Thermoelectric systems are feasible. However, total power available and the choice of working fluids both are critical to spacecraft integration and will be addressed later in this report.

To overcome the inherent limitations of existing propulsion technology for small satellites, recent research at the *University of Surrey* has focused on nitrous oxide[1] (N_2O). It is a colourless, non-toxic, liquefied gas with a slightly sweet taste and odour. It is non-corrosive and may be used with common structural materials. Nitrous oxide is stable and comparatively unreactive at ordinary temperatures, e.g. to ozone, hydrogen, the halogens, the alkali metals, etc. [Brak 80] It is decomposed into nitrogen and oxygen by heating above 520°C. [Dain 96] Chemical composition of the decomposition products ($36.3\%O_2$ + $63.7\%N_2$) is akin to that of air. The decomposition reaction can be accelerated by a catalyst. At elevated temperatures nitrous oxide supports combustion and oxidises certain organic compounds, the alkali metals, etc. [Brak 80] Nitrous oxide is classified by the Department of Transportation as a non-flammable, compressed gas and is shipped with the required "Green Label". [Brak 80]

Three basic properties of nitrous oxide make it attractive as a multi-purpose rocket propellant:

- Can be stored as a liquid (~745kg/m^3) with a vapour pressure of ~52bar (at 21°C)
- Decomposes exothermically with adiabatic decomposition temperature reaching ~1640°C
- Free oxygen available by decomposition can be combusted with a wide variety of fuels

[1] also known as "laughing gas", dinitrogen oxide, or dinitrogen monoxide

Taking advantage of these properties, especially the exothermic catalytic decomposition, space propulsion applications of nitrous oxide may be extended to:

- cold-gas propulsion for attitude control of a spacecraft
- monopropellant thruster for spacecraft station-keeping and small orbit manoeuvres
- bipropellant thrusters for large orbital manoeuvring
- power-generation on-board spacecraft or launch vehicle
- oxygen generation on board spacecraft

Since the whole range of propulsion functions can be covered by one self-pressurising propellant, multi-mode propulsion systems can be envisioned to satisfy a wide variety mission requirements. Such systems would employ different types of thrusters fed by nitrous oxide from a single, simply designed storage tank.

Nitrous oxide is not new to the propulsion community. Previously, the American Rocket Company (*AMROC*) used nitrous oxide as an oxidiser for its hybrid rocket motors. [SD 00] However, it has yet to be officially recognised as a rocket propellant, nitrous oxide is also used in amateur rocketry in combination with solid (polypropylene, hydroxyl-terminated polybutadiene (HTPB), asphalt, etc.) and liquid (alcohols, etc.) fuels. [RATT, LR 5, AIIR, Fink 98, FlTd 97] Surrey Space Centre's *Mark-IV* resistojet thruster uses this gas for orbit correction on the *UoSAT-12* mini-satellite. [Lawr 98, RJ, SSTL] The *Space Cruiser System,* a fully recoverable and reusable piloted passenger carrying sub-orbital space-plane, is planned to use three nitrous oxide/propane pressure fed, rocket engines. [SC, SVVD]

This report introduces nitrous oxide as a multi-purpose propellant for spacecraft. The advantage of employing this propellant on small spacecraft is shown in the following performance comparison of different thruster types.

4.1.1 Storage System

Nitrous oxide is a storable propellant that does not require an expulsion system. When in a pressurised tank, it exists in two forms, liquid and gas. At room temperature the pressure of a full tank, regardless of size, will read approximately 52bar. Since nitrous oxide is a liquefied gas, the pressure will remain constant as long as any liquid remains in the tank. When the tank has been used to the point where a liquid phase no longer exists (after approximately 75% to 80% consumption), then the pressure will start to drop.

Above its critical temperature 36.5°C nitrous oxide will convert completely to a gas and the discharge of the tank content will show a steady drop in pressure. [Brak 80]

Pressure of gaseous nitrous oxide can be calculated by Benedict-Webb-Rubin (BWR) equation of state within temperature range from -30°C to 150°C, for densities up to 900kg/m^3, and maximum pressure of 200bar. [Wala 85]:

$$P = RT\rho + \left(B_0 RT - A_0 - \frac{C_0}{T^2}\right)\rho^2 + (bRT - a)\rho^3 + a\alpha\rho^6 + \frac{c}{T^2}\rho^3\left(1+\gamma\rho^2\right)\exp\left(-\gamma\rho^2\right)$$

where P – gas pressure, atm;

R – universal gas constant $R=0.08206$ atm·L/mol/K;

ρ – gas density, mole/L;

T – gas temperature, K;

$A_0, B_0, C_0, a, b, c, \alpha, \gamma$ – gas constants of equation.
This equation is used to predict nitrous oxide pressure variation inside a storage tank as a function of temperature (see fig. 1 and 2).

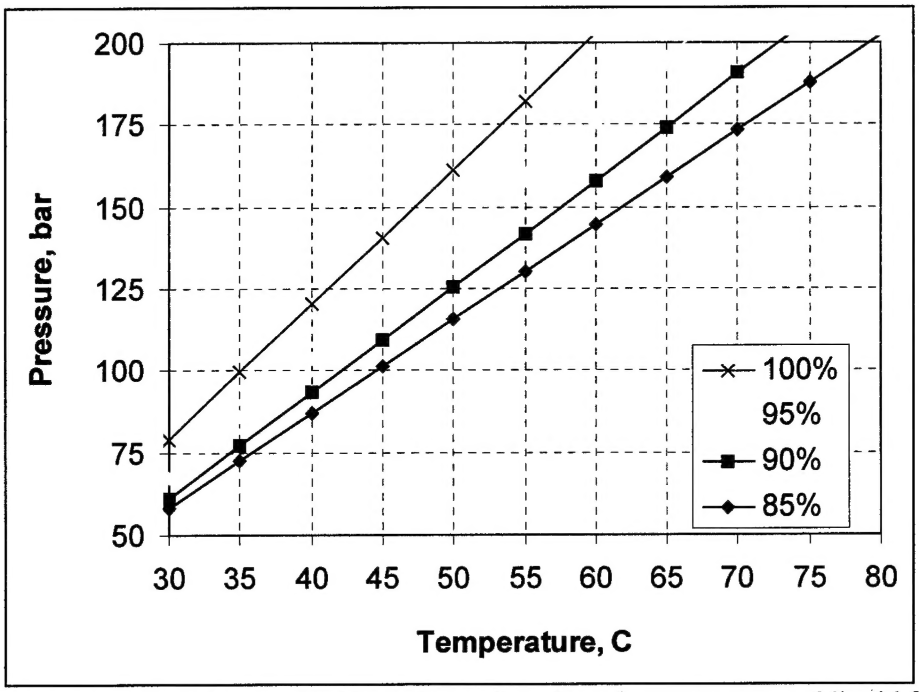


Fig. 1: Storage pressure of nitrous oxide tank as a function of temperature and liquid fill volume fraction (100, 95, 90, 85% @ 20°C).

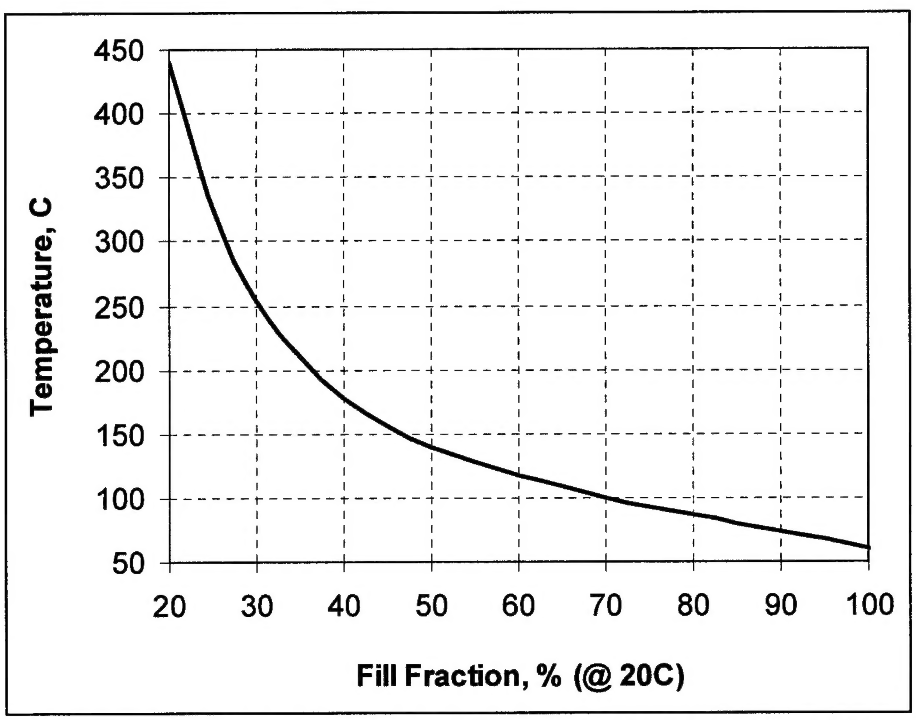


Fig. 2: Allowable storage temperature of nitrous oxide tank as a function of liquid fill volume fraction (@ 200bar).

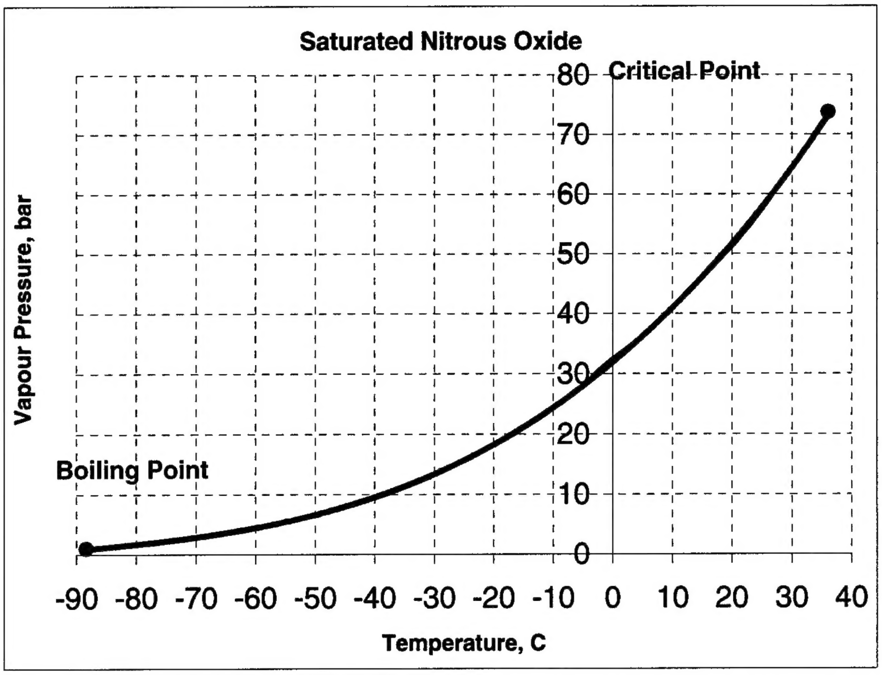


Fig. 3: Nitrous oxide vapour pressure as a function of temperature.

Chilling the tank lowers the pressure (and thus nitrous oxide flow rate) dramatically (as shown in fig. 3).

In general, nitrous oxide can be stored as liquid or compressed gas (above the critical point) through the wide temperature range limited perhaps by thermal decomposition temperature of 520°C on the upper end and the triple point on the lower end of the scale. [Brak 80, Dain 96] The maximum storage temperature limit is dependant on provisioned tank pressure and ullage volume. The practical maximum operational temperature number for designed tank pressure of 200bar would be 60°C. However, it increases while the propellant is consumed. The recommended low operational temperature is -34°C. This would allow tank operational pressure (i.e. nitrous oxide vapour pressure) stay above 11bar.

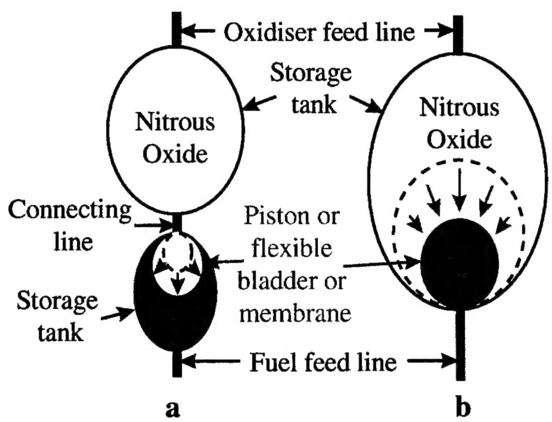


Fig. 4: Schematics of self-pressurising bipropellant system designs: a) separate tanks; b) single tank.

In bipropellant propulsion nitrous oxide vapour pressure may be used for pressurisation of liquid fuel. In this case two principal designs are possible: a) oxidiser and fuel are stored in separate but connected tanks; b) single storage tank is used for both propellant components (see fig. 4). Although at normal temperature combination of fuels with nitrous oxide is non-hypergolic, complete seal between the propellants must be insured to avoid their mixing – a cause of a potential explosion hazard.

Recent experience of storing nitrous oxide on-board the *UoSAT-12* mini-satellite for more than one year indicates that storage of the gas in-orbit is not a problem.

4.1.2 Decomposition

Nitrous oxide catalytic decomposition is considered at Surrey as a key-technology for mono- and bipropellants restartable in orbit.
In the past nitrous oxide decomposition has been extensively studied, both in the presence, and in the absence, of catalysts. [Zaki 00b]
The decomposition of nitrous oxide results in formation of nitrogen and oxygen according to the following reaction equation:

$$\mathbf{N_2O(g) \rightarrow N_2(g) + \tfrac{1}{2}O_2(g) + Heat}$$

At standard conditions this exothermic reaction generates ~82kJ of heat per mole of nitrous oxide. [Atki 97, Lide 95] However, heat input is required to initiate the reaction. In the case of thermal decomposition the activation energy barrier for nitrous oxide is about 250kJ/mole. [Atki 97] Therefore, in order to attain the required reaction rates, the gas must be heated to above 1000°C.
A catalyst lowers the activation energy barrier, and thus the decomposition occurs at much lower temperatures (>200°C). Fig. 5 illustrates the advantage of catalytic over thermal decomposition. Textbooks on catalysis and chemisorption often give nitrous oxide decomposition as an example followed by list of catalysts. [Clar 70, Kryl 70, Thom 68, Trap 55]
In the gas flow, if balance between rates of heat generated by decomposition and heat dissipated into surrounding is achieved ($\boldsymbol{Rate_{heat\ generated} - Rate_{heat\ dissipated} = 0}$) then the reaction becomes self-sustaining.

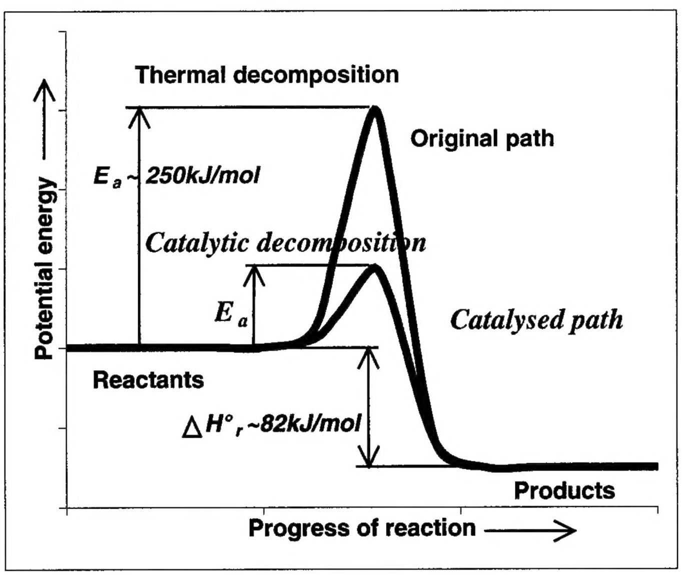


Fig. 5: Nitrous oxide decomposition. ($\boldsymbol{E_a}$ – activation energy; $\boldsymbol{\Delta H^\circ_r}$ – reaction enthalpy)

4.1.3 Previous Achievements

Previous nitrous oxide resistojet research accomplished at Surrey Space Centre demonstrated that [RJ, SSTL]:

- Nitrous oxide can be used as a resistojet propellant.
- It can be stored onboard a spacecraft for more than a year.
- Self-pressurising nitrous oxide feed system can be designed for a spacecraft.
- Common structural materials can be successfully applied for propulsion design.
- Self-sustaining nitrous oxide decomposition is achievable.

In particular, the results of work on low-power resistojets started at Surrey by Timothy Lawrence in 1995 report: [Lawr 98]

- The highest recorded specific impulse of the *Mark-III* nitrous oxide resistojet was 148s.
- During vacuum test of the *Mark-III* resistojet at the US Air Force Research Lab at *EDWARDS* Air Force Base, CA, nitrous oxide self-sustaining decomposition was observed for longer than 18 hours.
- The first (0.1N and 100W) nitrous oxide resistojet thruster *Mark-IV* has been successfully commissioned on board the *UoSAT-12* mini-satellite (see fig. 6).

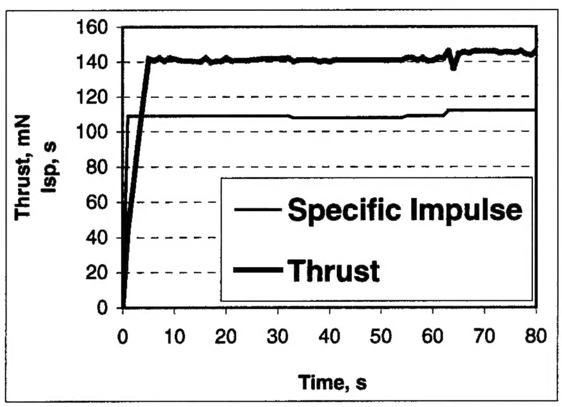


Fig. 6: Thrust and specific impulse for *UoSAT-12* resistojet firing on 11 April 2000.

4.1.4 Performance Comparison

4.1.4.1 Monopropellants

Theoretical specific impulse of nitrous oxide monopropellant thruster is evaluated using the *USAF ISP* computer code written by Curt Selph. The result of the computation is shown in fig. 7. The specific impulse monotonically rises with increasing decomposition temperature until it reaches its maximum (206s) at about 1640°C.

The performance of nitrous oxide monopropellant was compared with that of hydrogen peroxide and conventional hydrazine thrusters. (see table 1) The results reveal that a nitrous oxide monopropellant thruster is capable of moderate theoretical specific impulse performance, 16% lower than that of hydrazine but 15% higher than that of hydrogen peroxide thrusters. Each of these propellants can be

stored on board spacecraft. Although storage density of liquefied nitrous oxide is 26% lower than that of hydrazine and 45% lower than that of hydrogen peroxide, the low vapour pressure of these two propellants requires the use of a propellant expulsion system. An example of comparison results for total velocity change of satellite per propellant and pressurant mass is illustrated in figures 8 and 9.
The storage temperature range of nitrous oxide is discussed earlier in this report. In general, this range is broader than that of hydrogen peroxide and hydrazine. Storage temperature ranges for hydrogen peroxide vary as a function of its concentration. For the case of 89% strength hydrogen peroxide the low temperature limit is defined by a freezing point of -12°C. Five-degree margin between low operational limit and freezing point is a precaution against formation of slush. A similar estimate is applied to hydrazine that has a freezing point of about 2°C. The strong temperature dependence of hydrogen peroxide decomposition rate [JANN 84] limits its storage temperature to below 38°C. Since stainless steel is mildly catalytic to hydrazine at elevated temperatures the upper storage temperature below 60°C is recommended for this propellant.

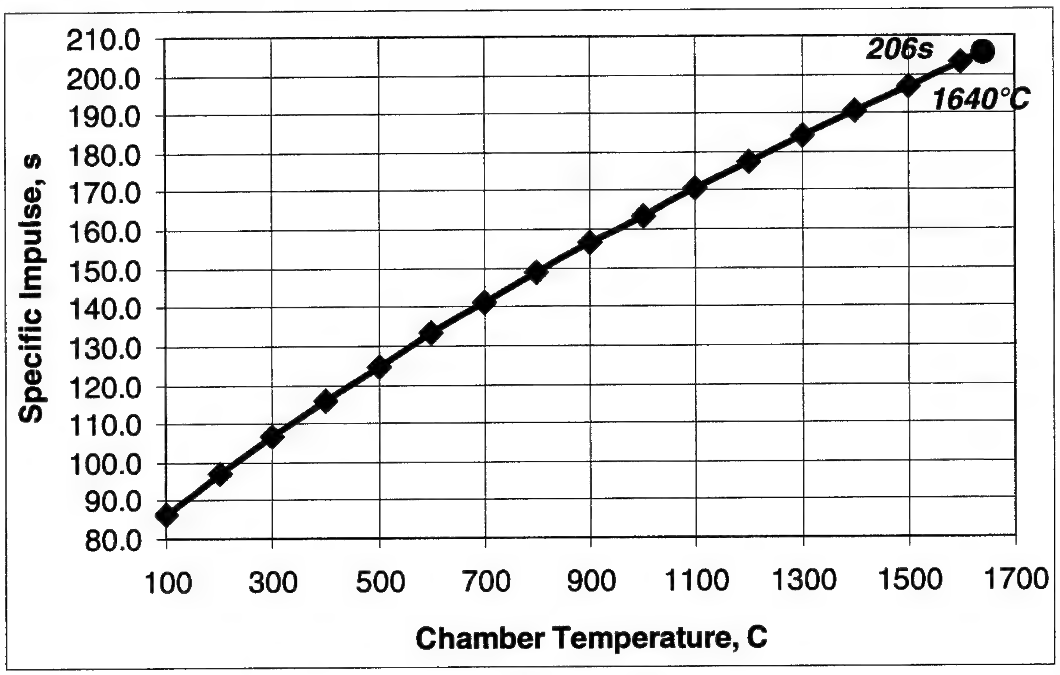


Fig. 7: Theoretical specific impulse of nitrous oxide monopropellant thruster as a function of chamber temperature (chamber pressure = 3bar; nozzle expansion ratio = 200).

TABLE 1: Properties of selected monopropellants.

Propellant	**Nitrous Oxide**	**Hydrogen Peroxide**	**Hydrazine**
Chemical Formula	N_2O	H_2O_2	N_2H_4
Specific Impulse (theoretical), s	206	179	245
Storability	Storable	Storable (decomposes)	Storable
Storage Density, kg/m³	745 @ 21°C 52.4 bar	1347	1004
Vapour pressure	50.8bar @ 20°C	0.00345bar @ 20°C	0.0214bar @ 26.7°C
Storage Temperature Range, °C	-34—60	-7—38	9—60
Toxicity	Non-toxic	Burns skin	Very Toxic
Flammability	Non-flammable	Non-flammable	Flammable
Flight Heritage	feed system UoSAT-12	flown	flown

Notes: All propellants are stored in liquid state. Hydrogen peroxide is 89% strength. Theoretical specific impulse data obtained for nozzle expansion ratio of 200.

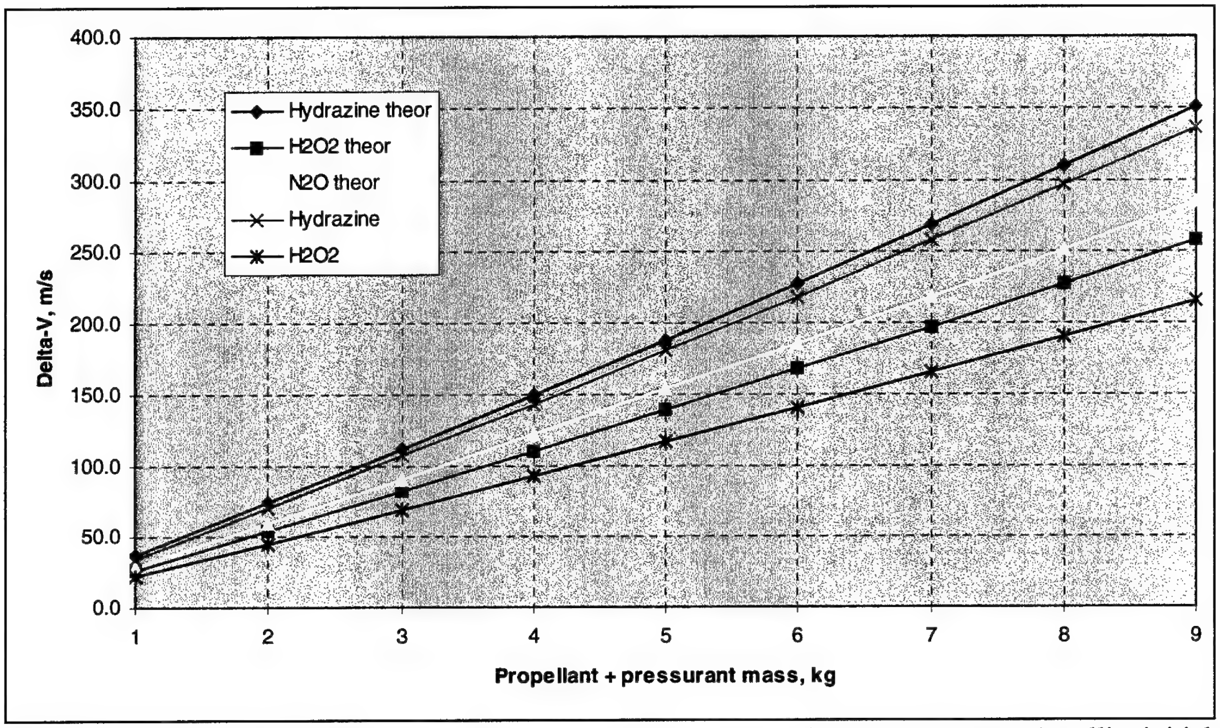


Fig. 8: Monopropellant performance comparison per propellant and pressurant mass. (satellite initial mass = 65kg)

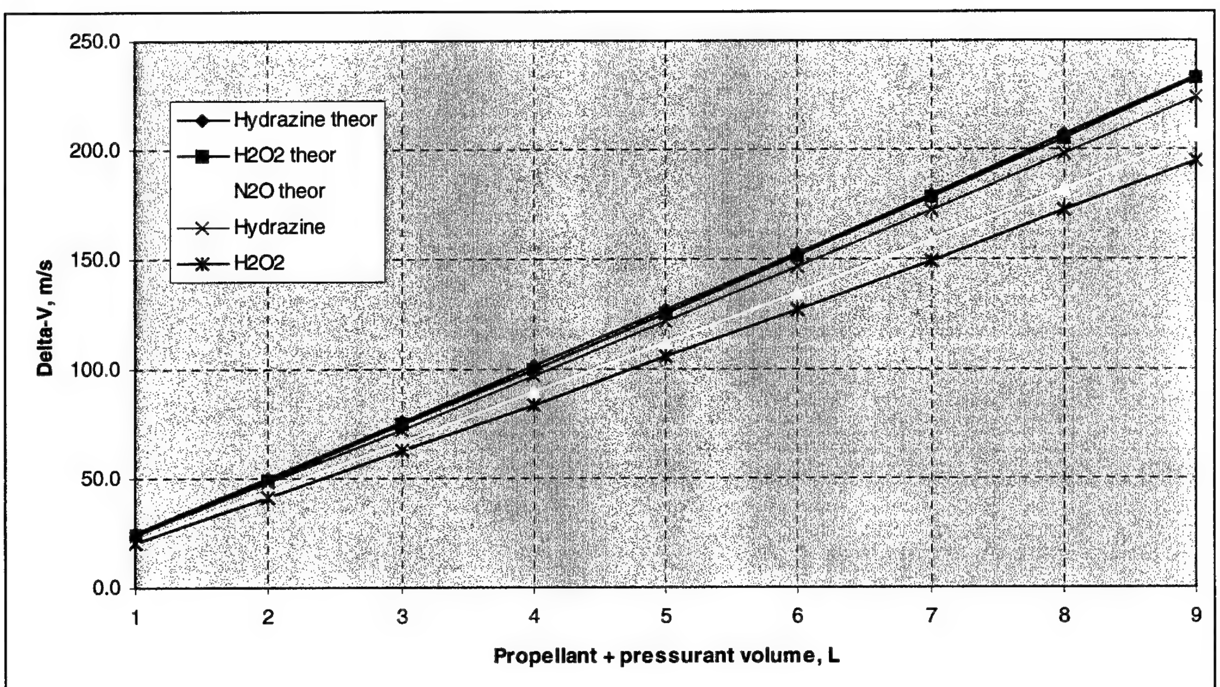


Fig. 9: Monopropellant performance comparison per propellant and pressurant volume. (satellite initial mass = 65kg)

a b c

Fig. 10: Protective handling equipment:
a) *UoSAT-12* Nitrous Oxide loading;
b) Chemical boiler suit for Hydrogen Peroxide handling;
c) *SCAPE* suits for Hydrazine and Nitrogen Tetroxide operations

In addition to raw performance, propellant handling is another significant issue to consider. Nitrous oxide handling requires minimal safety equipment (fig. 10a), while splash protection is necessary for hydrogen peroxide (fig. 10b). Complete protection is essential for hydrazine handling (fig. 10c). Nitrous oxide presents no fire or explosion hazard, while hydrogen peroxide may spontaneously ignite on contact with hydrocarbons. Contaminated hydrogen peroxide is unstable and presents a serious explosive hazard. High fire and explosion hazards are associated with hydrazine.
Although a nitrous oxide monopropellant thruster has yet to be flown, the feed system is currently under test on-board the *UoSAT-12* mini-satellite. Hydrogen peroxide monopropellant thrusters were employed on the number of missions. [McCo 65, Sell 96, Whit 98] Presently, hydrazine monopropellant thrusters are an extensively used space technology. [Sutt 92]

4.1.4.2 Cold-gas

Cold-gas propulsion is typically used for attitude control of the spacecraft because of the ability of such a system to provide a small minimum impulse bit. Ten common, easily available gases were selected for comparison. The results of the comparison are presented in figure 11. The gas storage conditions along with other properties for comparison are given in table 2.
Although nitrous oxide (along with carbon dioxide) provides the lowest theoretical specific impulse it has the second highest storage density amongst the selected cold-gas propellants. Therefore, it is able to deliver a higher change in total spacecraft velocity per unit volume of propellant (i.e. density Isp) compared with butane, propane, ethylene, methane, nitrogen, helium and hydrogen, all of which provide higher specific impulses but lower densities. Denser propellants are preferable for small satellites, which are volumetrically constrained by launch requirements as secondary payloads. Nitrous oxide has the third highest density Isp after ammonia and carbon dioxide.
Ammonia, however, is a toxic, highly reactive chemical that in combination with air may present an explosion hazard. Ammonia is incompatible with copper, tin, zinc and their alloys. Due to its high triple point, carbon dioxide may solidify in the feed lines and requires a thermal control system. Conversely, nitrous oxide is non-toxic, non-flammable; it has a low triple point and is compatible with common structural materials.

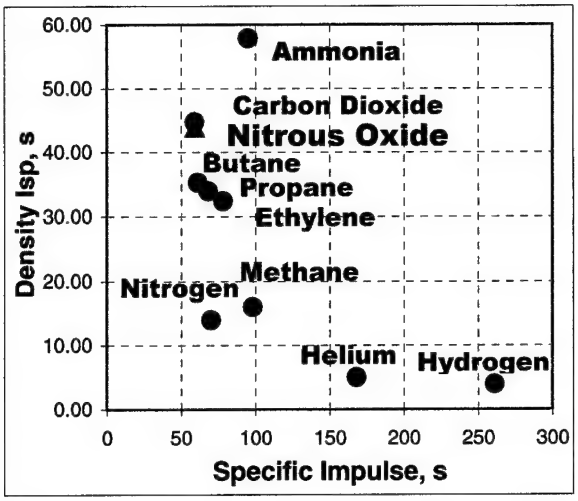


Fig. 11: Theoretical performance comparison of cold-gas propellants. (nozzle expansion ratio = 200)

TABLE 2: *Properties of selected cold-gas propellants.*

Name	Chemical Formula	Storage Conditions			Toxicity	Flammability	Remarks
		State	Density kg/m^3	Pressure bar			
Ammonia	NH_3	liquid	609	8.9	T	N	highly reactive
Butane	C_4H_{10}	liquid	578	2.2	N	F	non-corrosive
Carbon Dioxide	CO_2	liquid	758	58.9	N	N	not chemically active
Ethylene	C_2H_4	gas	415	202.7	N	F	non-corrosive
Helium	He	gas	30	202.7	N	N	inert
Hydrogen	H_2	gas	15	202.7	N	F	non-corrosive
Methane	CH_4	gas	163	202.7	N	F	non-corrosive
Nitrogen	N_2	gas	220	202.7	N	N	inert
Nitrous Oxide	N_2O	liquid	745	52.4	N	N	supports combustion
Propane	C_3H_8	liquid	499	8.6	N	F	non-corrosive

Notes: Storage conditions are taken at 21°C. T – toxic; F – flammable; N – non-toxic or non-flammable.

4.1.4.3 Resistojets

Heating a propellant in a resistojet improves specific impulse performance in comparison with cold-gas thrusters. Due to low heat transfer rates, resistojets are preferable for long duration firings. Therefore, orbit maintenance (or station-keeping) is a suitable function for such a thruster. Since power is the major constraint for electric thrusters on small spacecraft, specific impulse of several resistojet propellants is compared (fig. 12) by consumed energy. From that perspective, an *"ideal"* resistojet propellant for a small spacecraft would deliver the highest specific impulse at minimum input power. Therefore, it would locate itself towards top left corner of the figure. In this figure, a curve for more efficient propellant would be steeper then that of for a less efficient one. Ordinate axis of the graph corresponds to zero-power operational modes. Two of such modes are possible, when a resistojet is run as a cold-gas system, and when the heat generated as a result of initiated self-sustaining exothermic decomposition reaction is used. This latter feature can be described as a monopropellant mode.

From this figure, hydrogen is a good propellant because its basic high specific impulse grows fast with only little additional heating. However, its low density violates volumetric constraints for small satellite discussed earlier. The next best option would appear to be hydrazine.

Nitrous oxide resistojet is a special case. From the start, its performance almost overlaps that of nitrogen resistojet until self-sustaining decomposition is initiated. At that point, power input can be turned off, and the thruster will continue to operate as a monopropellant. Since the maximum temperature of nitrous oxide decomposition (~1640°C) is high, heating of its reaction products in resistojet is impractical due to the challenging choice of high temperature construction materials. Thus, the practical temperature operating range for nitrous oxide resistojet coincides with that of a monopropellant described above. The power savings associated with nitrous oxide catalytic decomposition in a monopropellant, however, support its use instead of resistojet.

On the whole, the specific impulse that can be delivered by hydrazine resistojet is higher than that of nitrous oxide resistojet or monopropellant. However, hydrazine toxicity and higher powers (>100W) required for such a resistojet might become prohibitive drawbacks for small satellite applications. In this case, the non-toxic nitrous oxide resistojet or monopropellant operating at zero-power mode are desirable.

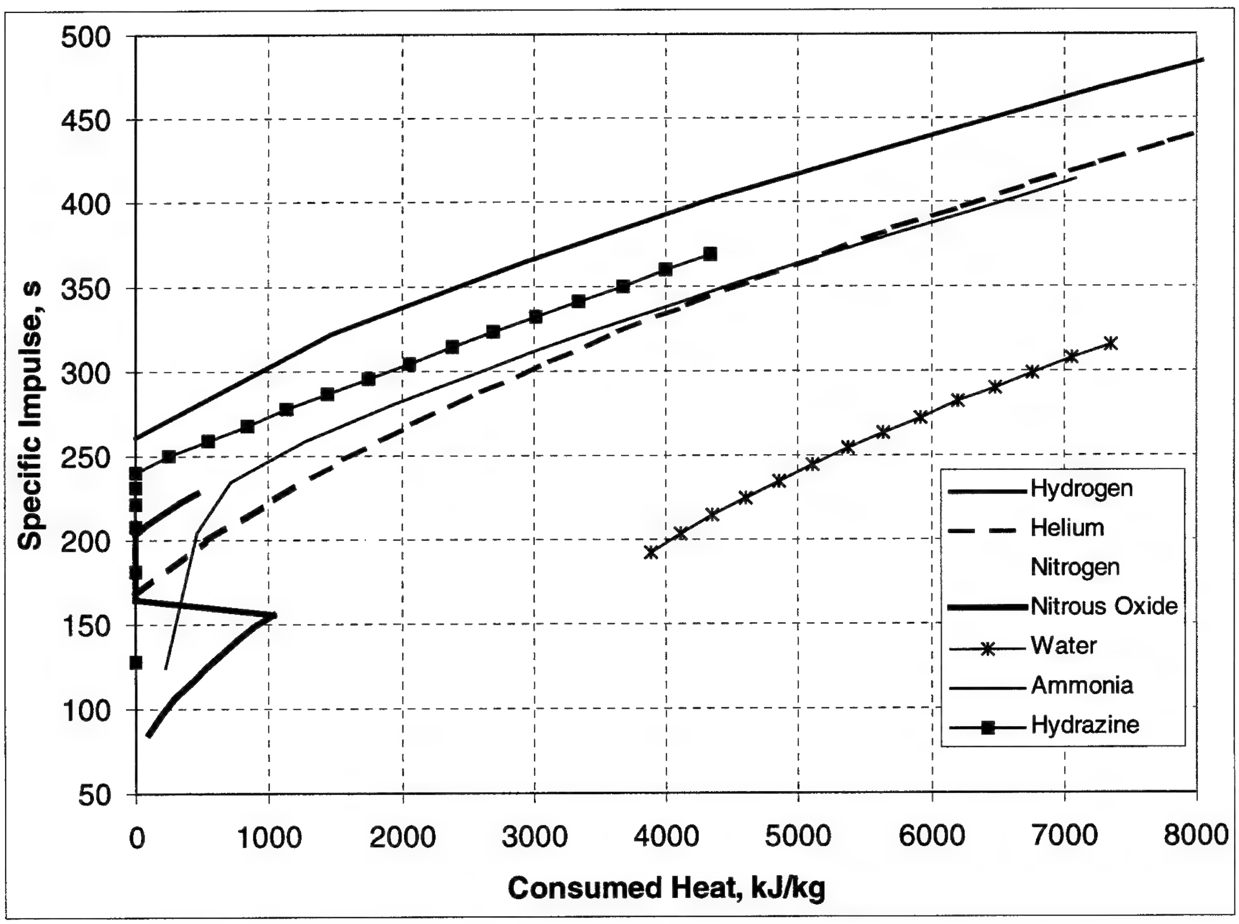
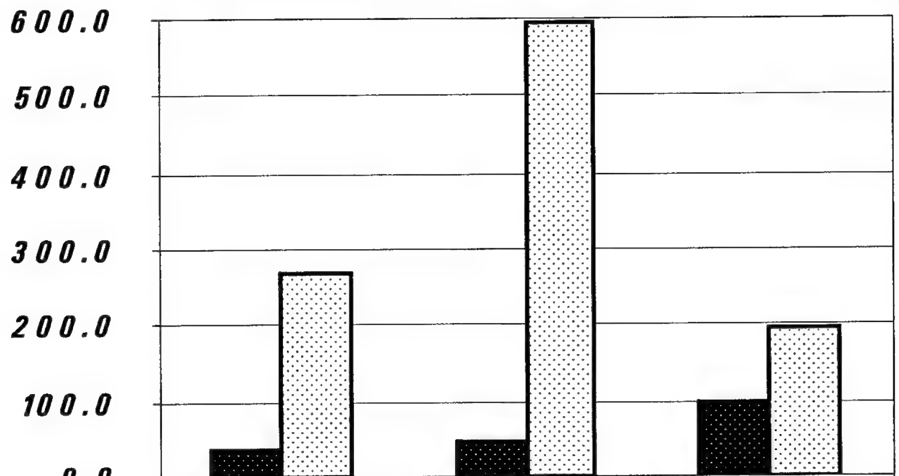


Fig. 12: Theoretical performance comparison of resistojet propellants: specific impulse vs. heat required for heating propellant to the process temperature.

4.1.4.4 Bipropellants

Generated by nitrous oxide decomposition, a hot nitrogen-oxygen mixture can be exhausted through a nozzle as a monopropellant or used to combust a fuel. The amount of free oxygen liberated in nitrous oxide decomposition is comparable to hydrogen peroxide, and pure gaseous oxygen (GOX) at 152 bar of storage pressure (see fig. 13). Although GOX has maximum mass fraction, available oxygen mass content bound in nitrous oxide and hydrogen peroxide is higher per unit of volume.



	N2O	89%wH2O2	GOX
Oxygen Content, %	36.3	44.1	100.0
Oxygen Mass Fraction, gm per 1L of propellant	271	595	198

Fig. 13: Amount of free oxygen available for combustion.

A hot nitrogen-oxygen mixture generated by nitrous oxide decomposition can be used to combust a fuel. Therefore, bipropellant thrusters employing nitrous oxide as an oxidiser are feasible.

Theoretical performance of several nitrous oxide bipropellant combinations has been evaluated to determine their feasibility for future applications. HTPB, PE and RP-1 are identified as three the most practical fuels for nitrous oxide bipropellants on small satellites and upper-stages. [Zaki 00a]

In fig. 14, the performance of these three is compared to conventional propellant combinations. Although the theoretical performance of the non-toxic bipropellants is somewhat lower than that of highly toxic conventional nitrogen tetroxide/hydrazine family propellant combinations it is still high enough (330s) to be considered for small satellite applications.

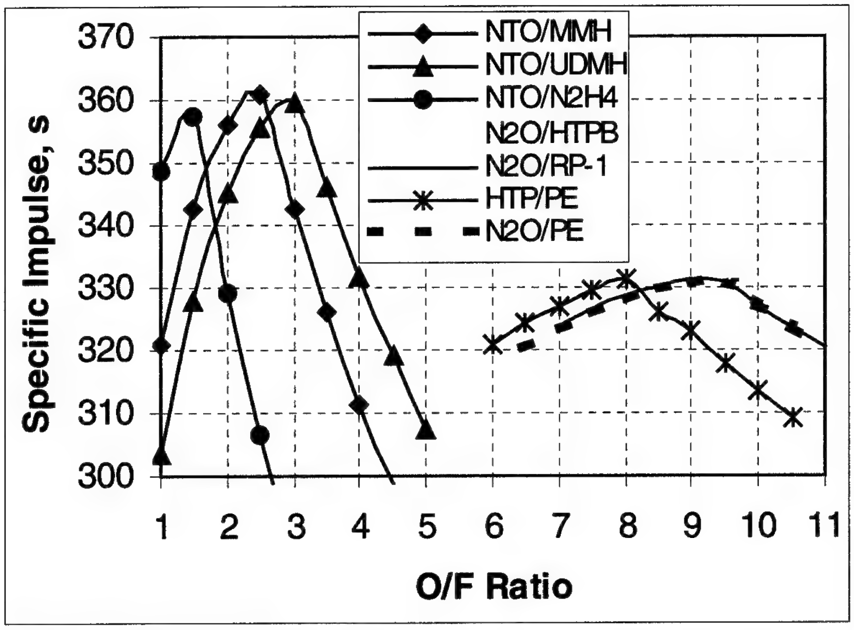


Fig. 14: Theoretical performance of bipropellant combinations[2] using nitrous oxide as an oxidiser. (The performance is calculated by USAF ISP computer code.)

4.1.4.5 Multi-Mode Propulsion System

For flexible small satellite missions, multi-mode propulsion systems are essential. Multi-mode propulsion systems are designed to offer a range of thrust and total spacecraft velocity change options to meet specific mission objectives, e.g. orbit insertion, station-keeping, and attitude control. While the use of nitrous oxide as a propellant may not be compelling when viewed in isolation for specific applications, its advantages over other propellant options in multi-mode systems become far more apparent. This is best illustrated by looking at a specific example that lends itself to an "apples-to-apples" comparison.

Triple-mode propulsion system (fig. 15) is taken out of a variety of possible multi-mode systems as an example. The propulsion system's mass and volume were analysed with respect to contribution of each mode to total spacecraft velocity change. The dual-modes in fig. 16 represent the extreme cases of triple-mode system analysis when contribution to total spacecraft velocity change by bi- or monopropellant mode vanishes. The triple-mode performance falls in between the performance of these dual-mode systems. The results of comparison are summarised in fig. 17. In this figure abscissa axis shows contribution of cold-gas mode fraction to total spacecraft velocity change. Ordinate axis

[2] HTPB – Hydroxyl-Terminated Polybutadiene
HTP – High Test Hydrogen Peroxide (here 89%w/w)
MMH – MonoMethyl Hydrazine
N2H4 – Hydrazine
N2O – Nitrous Oxide
NTO – Nitrogen Tetroxide
PE – Polyethylene
RP – Rocket Propellant (kerosene)
UDMH – Unsymmetrical DiMethyl Hydrazine

gives a ratio of total volume or mass of conventional to nitrous oxide propulsion system. When this ratio is equal to one the performance of conventional and nitrous oxide propulsion is the same. Below 1.0, the performance on conventional propulsion is better than that of nitrous oxide system. Above 1.0, the performance of nitrous oxide is superior over that of conventional system.

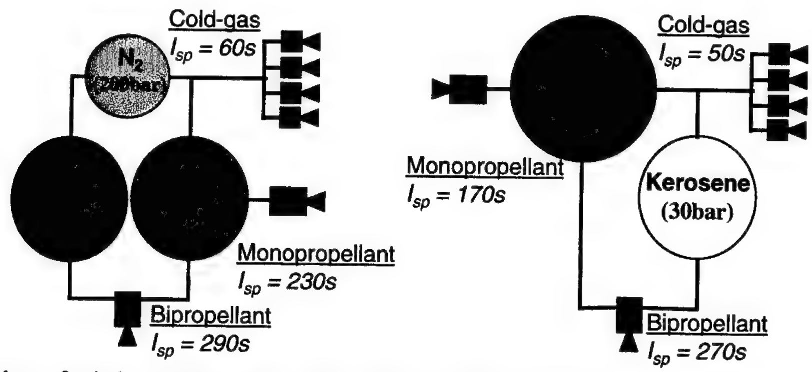


Fig. 15: Schematics of triple-mode propulsion system options for a small satellite.

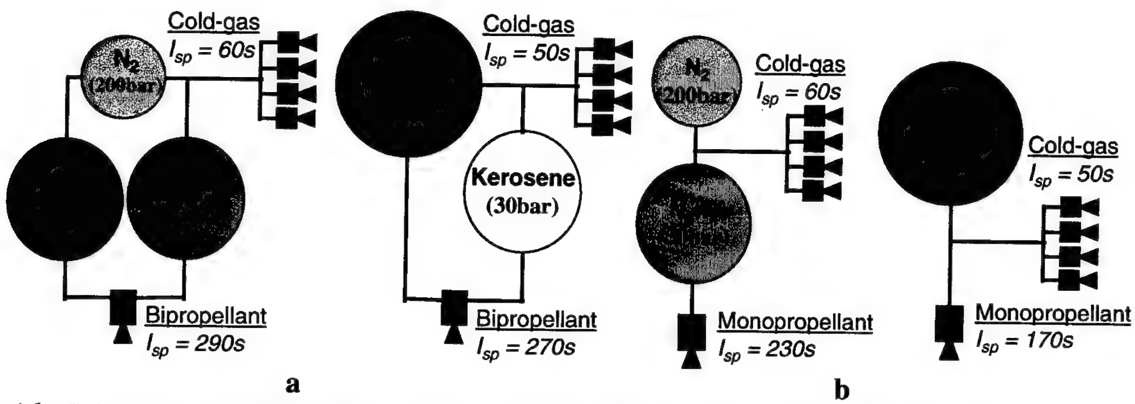


Fig. 16: Schematics of dual-mode propulsion system options for small satellite: a) Col-Gas/Bipropellant; b) Cold-Gas/ Monopropellant.

The graph shows that:

- For the most of the range total volume and mass of triple-mode propulsion using nitrous oxide is lower than that of an alternative conventional system.
- Both parameters improve with increasing cold-gas propulsion fraction.
- Application of nitrous oxide propulsion is more advantageous over conventional system in the case of cold-gas/bipropellant mode.

Therefore, the application of nitrous oxide triple-mode propulsion system is beneficial for cold-gas fraction at which its total volume and mass is lower than that of an alternative conventional system.
The particular numbers can be read on the graph. Although these numbers are the attributes of the particular design and, thus, may change drastically the tendency will still remain.
On the whole, the non-toxic nitrous oxide system is of simpler design than that of using toxic hydrazine propellant.
In the case of the nitrous oxide system, the propellant may be used till depletion by either mode with no restrictions except a provision required for total spacecraft velocity change. Meanwhile, in the case of hydrazine, margins for use of the propellants by each mode must be imposed. Hence, application of nitrous oxide system would give an important advantage of the flexibility in firing strategy during

mission. Therefore, since the propulsion requirements are more relaxed for nitrous oxide systems a number of considered in orbit mission scenarios can be increased. This feature is important especially for a spacecraft launched as a secondary payload since launch itself is often undefined until a few months to the launch date.

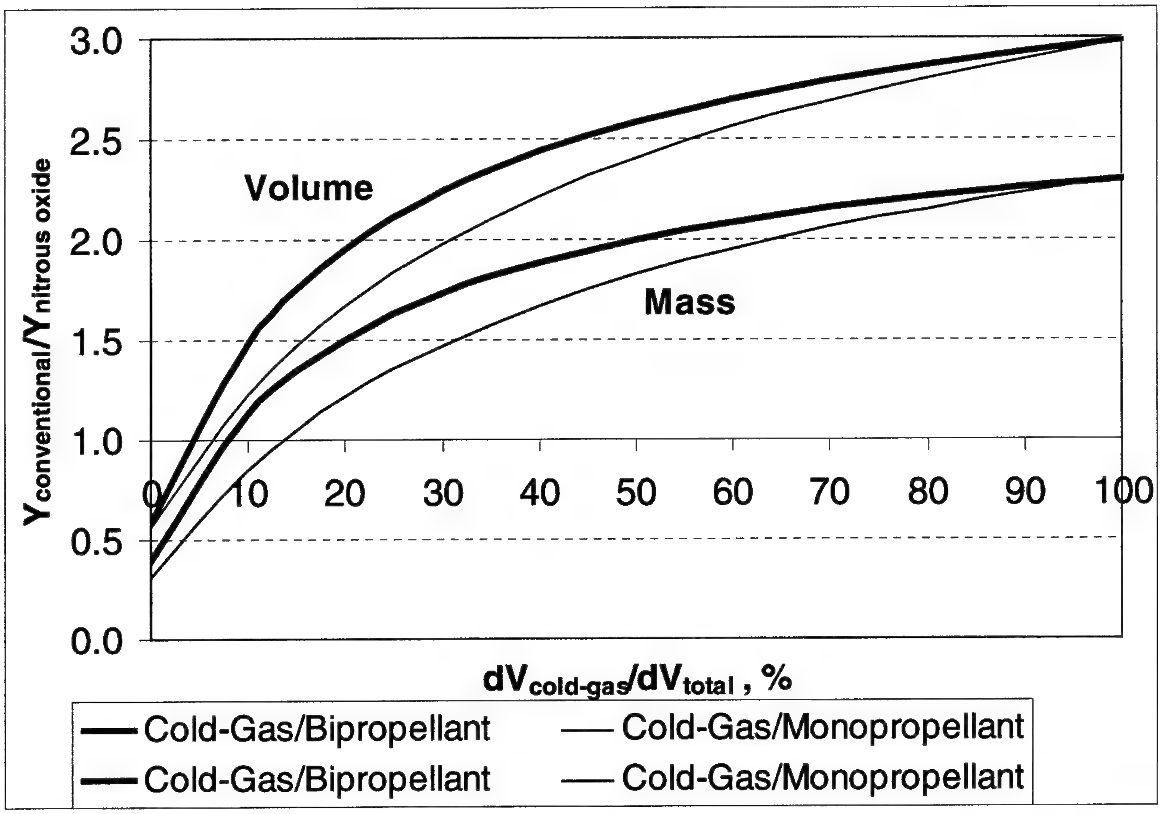


Fig. 17: Performance comparison of conventional vs. nitrous oxide propulsion. (**dV** – spacecraft velocity change; **Y** – denotes propulsion mass or volume respectively)

4.1.4.6 Conclusion

While not delivering the best specific impulse performance as a single-mode, nitrous oxide as a multi-mode, self-pressurising propulsion system simplifies the design and may provide higher total spacecraft velocity change and/or reduce mass. In addition, a nitrous oxide multi-mode system will benefit from non-toxicity, non-flammability and compatibility of the propellant in comparison to conventional hydrazine propulsion. Propulsion packaging and integration of such a system into spacecraft are easier. Flexibility of the firing strategy gained with a nitrous oxide multi-mode system increases the number of mission scenarios as well as launch opportunities.

5. MONOPROPELLANT THRUSTER CONCEPT

The schematics of a nitrous oxide monopropellant thruster employing catalytic decomposition is shown in fig. 18. In this device a flow of nitrous oxide is injected into the decomposition chamber. Upon injection, nitrous oxide starts to decompose on an electrically heated catalytic wire. The heat generated by decomposition activates the main catalyst, which in turn decomposes more nitrous oxide, and generates more heat. The process proceeds with increasing temperature until all of the catalyst is activated and the rate of decomposition reaches its maximum when steady state is achieved. This takes a few seconds. The products of the decomposition leave the chamber through the converging-diverging nozzle generating thrust. Once self-sustaining nitrous oxide decomposition is achieved, the electrical power input is no longer required.

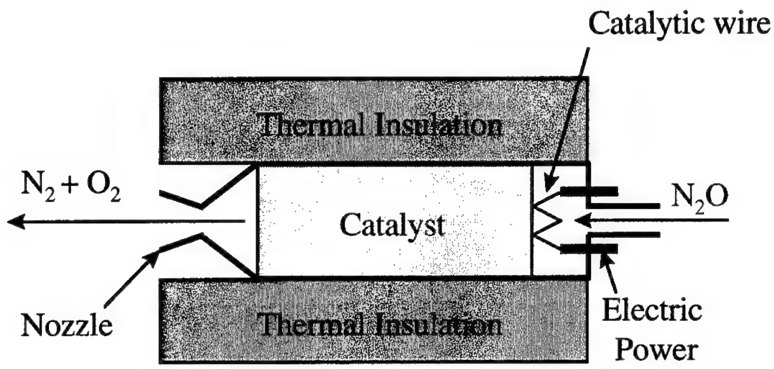


Fig. 18: Nitrous oxide monopropellant thruster schematics.

The suggested concept offers significant electrical power savings because:

- It makes use of catalytic decomposition providing considerable input power savings for reaction initiation over thermal decomposition technique employed in a resistojet
- It takes an advantage of self-sustaining decomposition as zero input power main operation mode for a thruster

This is expected to make nitrous oxide propulsion a feasible option for small satellites, extending its application range from mini-satellite (100-500kg) to micro-satellite (10-100kg) platforms.

Since low thrust levels (<1N) and, thus, low propellant mass flow rates (<0.5gm/s) are of interest, it is suggested to reduce thruster's operating chamber pressure to below 3bar. The lower chamber pressure is desirable for several reasons:

- The famous Le Chatelier's principle [Atki 97] can be interpreted as: "for chemical reaction with increasing volume of products lower pressure will shift equilibrium towards reaction products". In other words, lower pressure is beneficial for nitrous oxide decomposition.
- It increases the thuster's nozzle throat to the size that is easy to manufacture.
- It improves thrust efficiency since flow friction losses in the thuster's nozzle throat are reduced.
- Higher nitrous oxide storage tank depletion can be achieved.
- Taking in account low mechanical (due to lower pressure) and moderate thermal (due to "slow" start-up) stresses exerted on thruster's casing it would be possible to use high temperature ceramic materials (such as, for example, alumina) for its design. Application of high temperature ceramics in thruster design will shift operating temperature and, thus, improve the specific impulse performance.

Slight increase in thruster size and mass due to lower operating pressure is not crucial for low-thrust propulsion system, and is a subject of optimisation.

5.1 Test Apparatus

As a first step towards the development of flight-qualified thruster the following simple test apparatus was designed. A 190mm-piece of 25.4mm-inner-diameter stainless steel pipe was adopted to house the catalysts. The test apparatus design is shown in fig. 19. Later this thruster melted during a test run when nitrous oxide decomposition reaction temperature exceeded melting point of stainless steel.

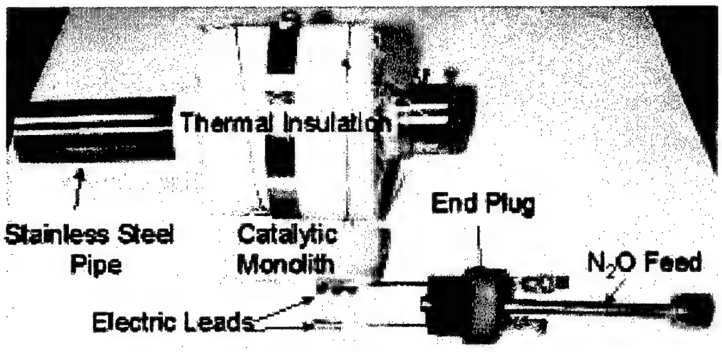


Fig. 19: Test design #1 (non-choked).

Second design (fig. 20) had a replaceable thick wall (3mm) 15mm (i.d.) stainless steel pipe housing the catalyst. Therefore, in the case of accidental pipe melting it could be easily replaced. However, due to a loose fit nitrous oxide leaked out of the apparatus. Since the parts had high thermal mass, excessive heat loss occurred due to heat transfer through the metal. For these two reasons the design was abandoned. *Shapal-M* aluminium nitride machinable ceramic was used for electric insulation. Silicate glue was applied as a sealant. However, the glue failed to work because of high temperature of connecting parts due to excessive heating.

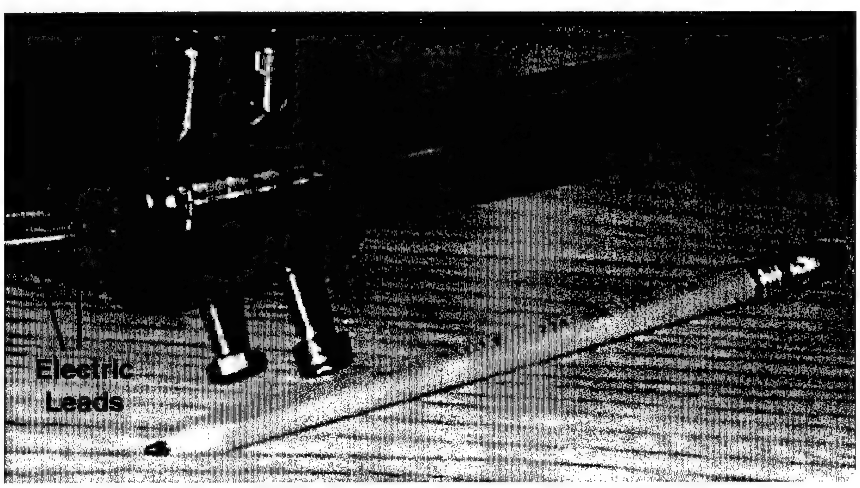


Fig. 20: Test design #2 (non-choked).

Third design (fig. 21) has a thin wall (1.5mm) 15mm (i.d.) stainless steel pipe housing the catalyst made as one piece with a flange. A copper seal ensures against gas leaking. A spacer is designed to raise catalyst up from the flange and prevent heat loss to the flange. Ceramic mastic first used for electric insulation and sealing, was later replaced by screwed-in standard electric feedthroughs DLT4/LT/XH manufactured by OXLEY Ltd. The features of this design are quite satisfactory.

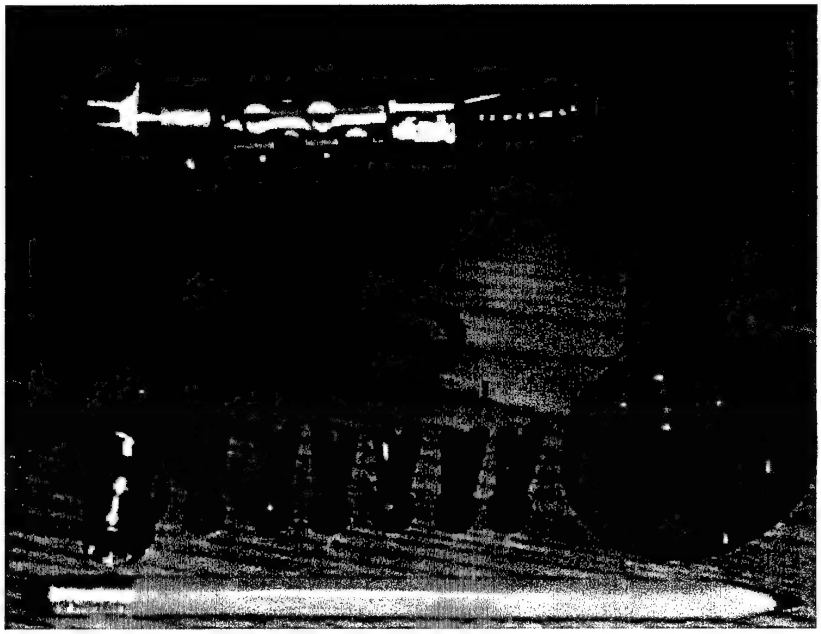


Fig. 21: Test design #3 (non-choked).

In the fourth design (25mm i.d.) nitrous oxide flow is choked by converging nozzle of 0.5mm diam. Technical drawings for this design are given in appendix A.

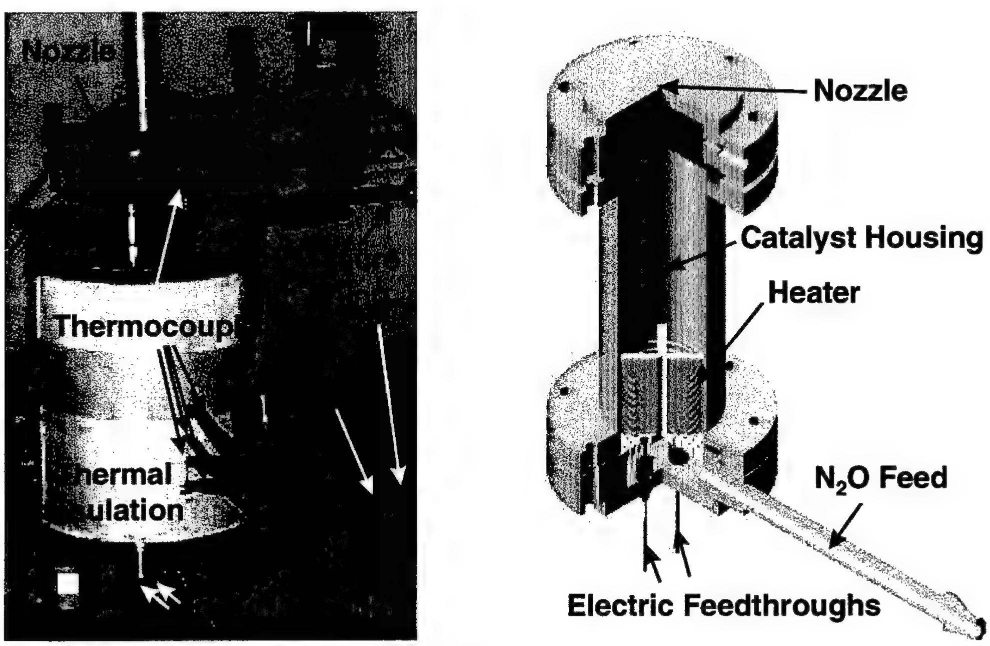


Fig. 22: Test design (choked).

Designs 3 and 4 are currently the base-line apparatus used for catalyst and decomposition testing.

5.2 Test Set-up

Experimental set-up for nitrous oxide decomposition research is shown in fig. 23 and 24. Gaseous nitrous oxide from the cylinder flows though the valve and regulators to the test apparatus where it decomposes on a catalyst before discharging to atmosphere. A pressure gauge and flow meter in the nitrous oxide feed line indicate flow parameters set by the regulators. Direct current power supply is necessary for heating a catalytic wire inside the apparatus. Thermal insulation is used to reduce heat loss from the decomposition chamber.

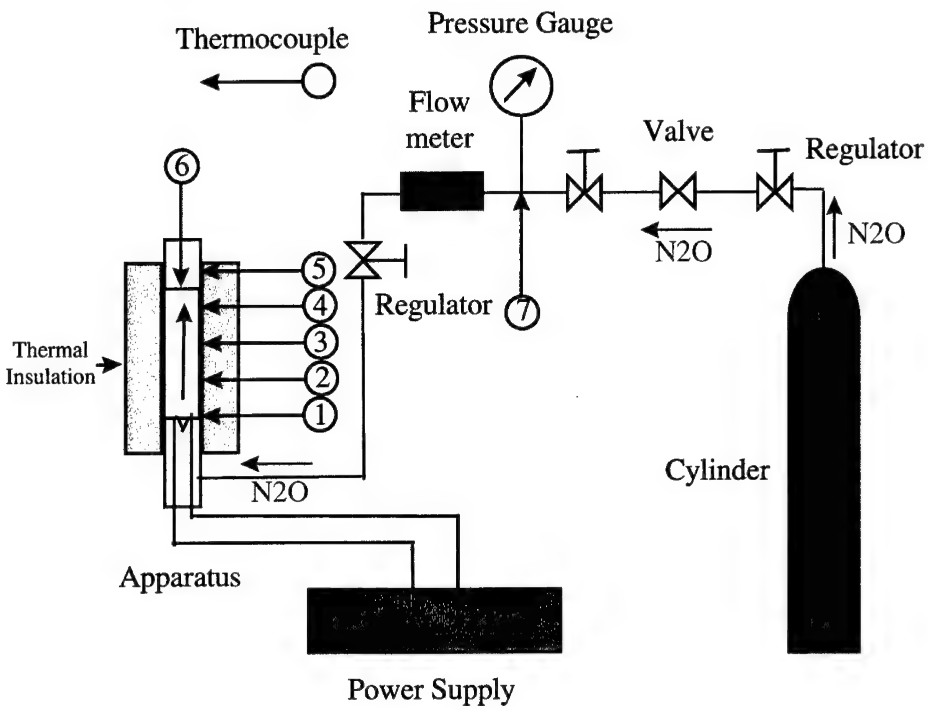


Fig. 23: Test set-up for non-choked flow (Thermocouple *6* is set to read the temperature of exhaust gases. Thermocouples *1, 2, 3, 4* and *5* are set to measure decomposition chamber outside wall temperature. Thermocouple *7* is set in stream of nitrous oxide feed line).

5.3 Equipment and Instrumentation

Medical Grade nitrous oxide was supplied by BRITISH OXYGEN COMPANY (BOC).
Test data were processed by DELL Pentium-III 666MHz computer.
NATIONAL INSTRUMENTS LabVIEW v.5.0 software along with acquisition PCI-6024E board was used for data collection.
R-type in-flow thermocouple reading was taken by DATATRACK PROCESS INSTRUMENTS Ltd. Tracker 220.
K-type low cost thermocouple transmitter were bought from Labfacility Ltd. And calibrated from 0 to 1000°C by RS 180-7098 K-thermocouple simulator (RS Service point Calibration and Repair Service).
0-6 and 0-10bar VEGABAR 14 pressure transmitters by VEGA Controls Ltd. were use for sampling pressure.

Omega FMA5612-I series gas flow-meter 0-30 SLPM range calibrated for air. The conversion factor 0.71 was applied for nitrous oxide gas to get actual value (as suggested by the flow-meter manual). Nitrous oxide in-flow temperature and pressure through the flow-meter were measured.
The in-flow temperature 21-22°C stayed constant during 15min. run. 0-6 bar VEGABAR 14 pressure transmitter available for pressure measurement was not sensitive enough to detect in-flow pressure change.
DC electric current was provided by TTi standard TSX series 0-35V, 10A power supply.

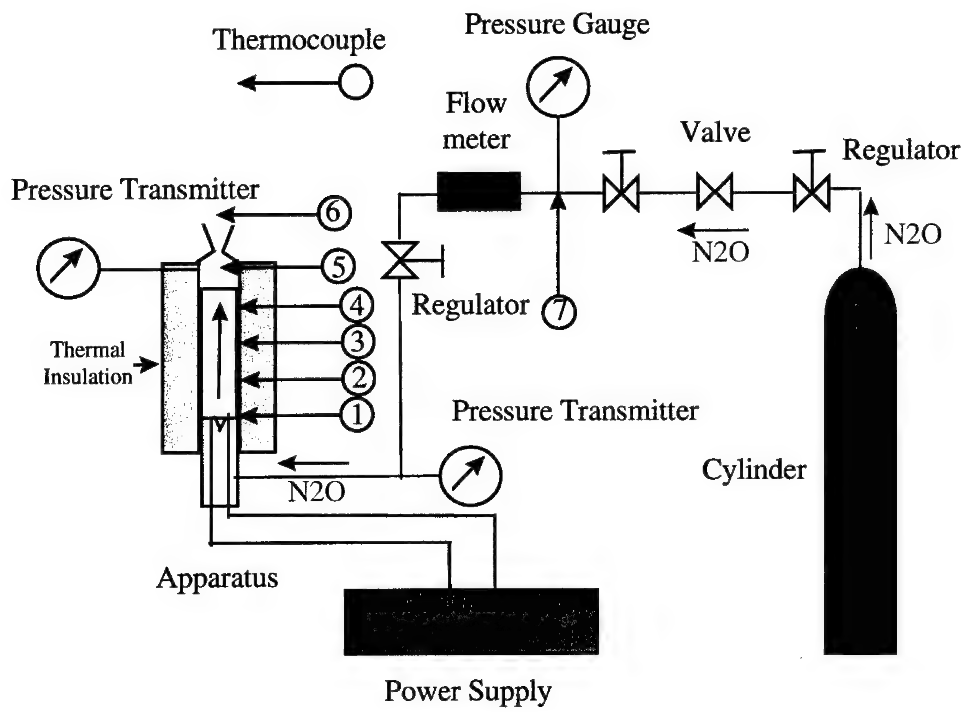


Fig. 24: Test set-up for choked flow (Thermocouples *5* and *6* is set to read the temperature of exhaust gases. Thermocouples *1, 2, 3,* and *4* are set to measure decomposition chamber outside wall temperature. Thermocouple *7* is set in stream of nitrous oxide feed line. Pressure gauges are set to read upstream and downstream pressures).

6. EXPERIMENTAL RESULTS

Experimental results presented cover catalytic wires, decomposition catalysts, flow-controlled self-sustaining decomposition, input power requirements, and summary. Total number of test runs is 108. Supporting information and data for the test results discussed in this report are given in appendix B.

6.1 Catalytic Wires

Table 3 lists metals and metal alloys successfully used for nitrous oxide decomposition initiation (catalytic wires). Due to their relatively low melting points and oxidation resistances stainless steel

and nickel/chromium alloy wires have short lifetime (few firings), and, therefore, require frequent replacement meanwhile rhodium and thermocouple wires have long lifetime due to their high melting points and oxidation resistances. However, low electrical resistances of rhodium and thermocouple wires require higher electric currents that are inconvenient to supply. In addition they are much more expensive. Since stainless steel and nickel/chromium alloy wires are cheap, they are used for tests. For flight model of the thruster thermocouple wire is recommended. Although giving the best performance rhodium wire is hard, and difficult to obtain.

TABLE 3: *Catalytic wires*

Wire Material	Melting point °C	Advantages	Disadvantages
Rhodium	1966	Very good catalytic activity High melting point Oxidation resistant at high temperature	Low electric resistance Hard Very expensive
Platinum/Rhodium thermocouple wire (70%Pt/30%Rh; 87%Pt/13%Rh; 94%Pt/6%Rh)	 1920-1930 1840-1865 1825-1835	Good catalytic activity High melting point, Malleable Easy available Oxidation resistant at high temperature	Low electric resistance Expensive
Nickel/Chromium alloy (80%Ni/20%Cr)	1400	High electric resistance Easy available Inexpensive Malleable	Relatively low melting point Low oxidation resistance at high temperature
Stainless steel	1350 – 1500	Good electric resistance Easy available Inexpensive Malleable	Relatively low melting point Low oxidation resistance at high temperature

6.2 Decomposition Catalysts

More than 50 different catalysts were tested for nitrous oxide decomposition. The most complete record of these catalysts is given in appendix C. Several iridium, platinum, and nickel oxide catalysts on different oxide substrates donated by the chemistry department are not listed in this table for two reasons.

- The information about the catalysts is considered to be a proprietary one.
- The catalysts did not show good activity in nitrous oxide decomposition.

Among the listed catalysts there are three identified as the most promising ones.

- Mix of nickel oxide (NiO) pieces with nickel oxide coated zirconia (ZrO_2) pieces
- Shell 405 or LCH-212
- Rhodium oxide (Rh_2O_3) coated gamma alumina (γ-Al_2O_3) pellets

High nitrous oxide decomposition temperature above 1500°C was achieved using mix of nickel oxide with nickel oxide on zirconia. During two consecutive tests of this catalyst the temperatures as high as 1288°C and 1538°C were recorded respectively. However, since the activation temperature is high (500°C) the decomposition initiation requires a lot of heating. In addition, since the rest of the parts of concurrent design were made of stainless steel tests always ended up with a failure of heater or stainless steel gauze screen holding catalyst downstream. It is suspected that chemical reaction of

oxidation of stainless steel is indeed responsible for the highest temperature reading. Another difficulty is the fact that the catalyst is homemade. The manufacture process includes baking of the catalyst pellet, and then breaking it by smashing in pieces. Such a crude process provides catalyst pieces of irregular shape and size. Therefore, there is no control over catalyst surface. The difficulty of obtaining repeatable results with such a catalyst is anticipated. For these reasons this catalyst is temporary abandoned until the development of technology capable of manufacturing of predictable surface area catalyst.
Both Shell 405 and LCH-212 are very active catalysts for nitrous oxide decomposition. Due to high content of catalyst material (iridium oxide) on alumina substrate this catalyst is capable of supporting high flows of nitrous oxide. The activation temperature of these catalysts is between 400-450°C. At temperatures above 1100°C iridium oxide catalytic material sublimates and is blown out of catalyst chamber. It redeposits itself on in-flow thermocouple. Unfortunately, the limited supply of these catalysts at Surrey Space Centre is close to depletion. Limited finances eliminate the option of buying the catalyst. Currently we are looking for opportunity of donation of some catalyst to us for further research.
Rhodium oxide coated on alumina pellets is a catalyst of current investigation. Its catalytic activity is higher than that of Shell 405 and LCH-212. At lower catalyst content on substrate surface it supports higher flows. Its activation temperature is 250°C. Hence, it requires less heating. Unfortunately, rhodium oxide decomposes at 1100°C, therefore the operational temperature for this catalyst is provisioned within 900-1000°C.
Combined catalyst of pieces of rusty metal placed on top of rhodium oxide coated alumina pellets achieved extremely high decomposition temperature that melted stainless steel casing holding the catalyst. Although this catalyst demonstrated high temperature potential of nitrous oxide decomposition it cannot be used for restart since rusty metal pieces melt. Chemical reaction of metal oxidation (combustion) is suspected to cause stainless steel casing melting.
In our search for high performance high temperature stable catalysts for nitrous oxide decomposition catalyst departments of Degussa-Huls and Johnson & Matthey have been approached.

6.3 Flow-Controlled Self-Sustaining Decomposition

The ability of nitrous oxide decomposition reaction control by changing the flow rate of the gas was demonstrated (fig. 25). During the test after power cut-off, temperature on exhaust flow of the gas (tc6) was changed up and down, and up and down again by varying nitrous oxide flow rate. Fig. 26 shows how the measurements were taken. Thermocouple locations are shown on fig. 23.
Other results suggest that final (steady-state) exhaust gas flow temperature of decomposition reaction products for each particular design is a function of nitrous oxide mass flow rate. Figure 27 demonstrates that higher mass flow rates correspond to higher temperature of exhaust gas flow.
In fact, analysis of this data shows (fig. 28) that the relationship is linear within flow rate range tested. This relationship corresponds to the following equation:

$$T_{\text{decomposition}}\ [^\circ\mathrm{C}] = 6974.144 \times \underline{\text{mass flow rate}}\ [\mathrm{gm/s}] + 440.7826$$

Moreover, it is suggested that <u>the final (steady-state) exhaust gas flow temperature of decomposition reaction products for each particular design is a function of nitrous oxide mass flow rate only</u>. Figure 29 shows for two different mass flow rates that despite significant differences in input power exhaust flow gas temperatures tend to saturate at the same temperature.

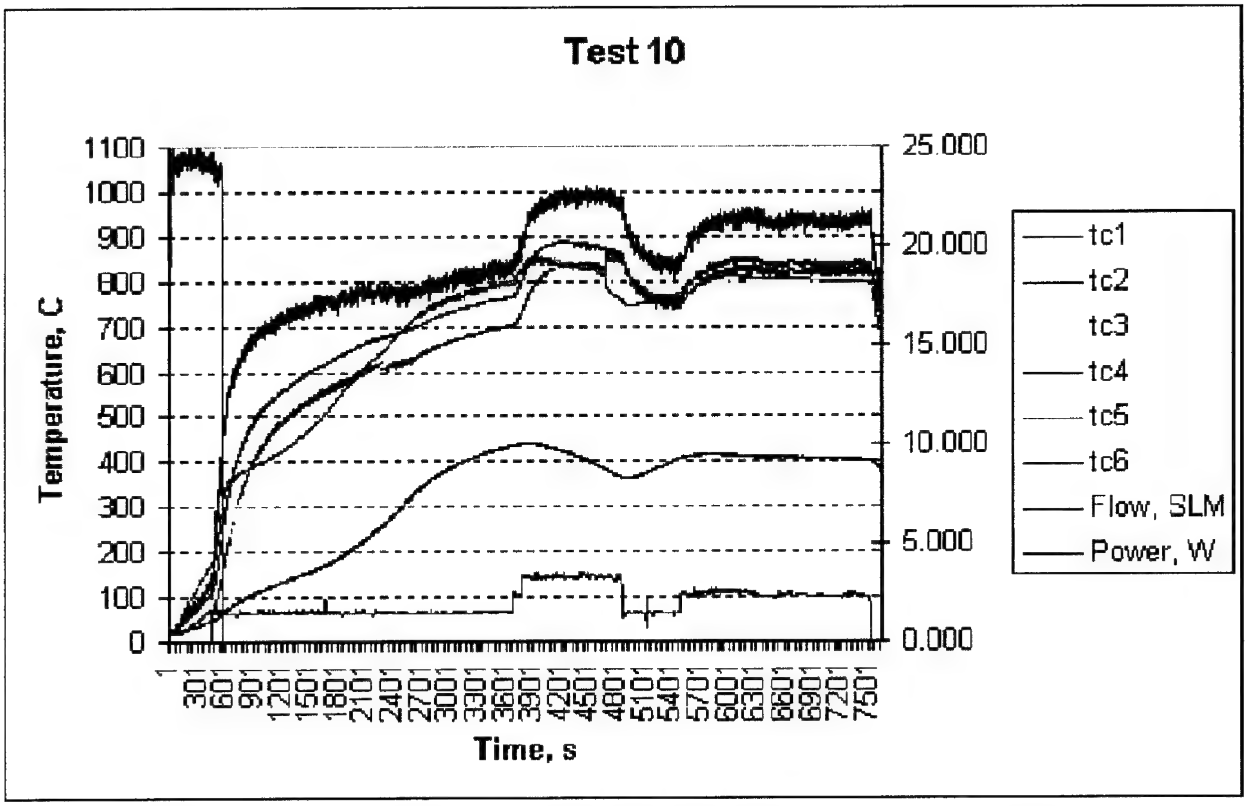


Fig. 25: Flow-Controlled Self-Sustaining Decomposition of Nitrous Oxide.

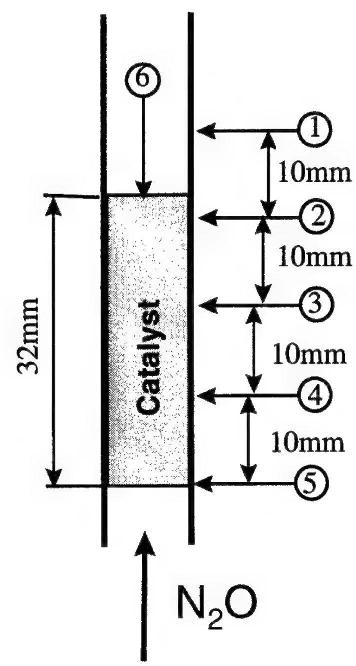


Fig. 26: Sketch of temperature measurement for test 10 (design #3).

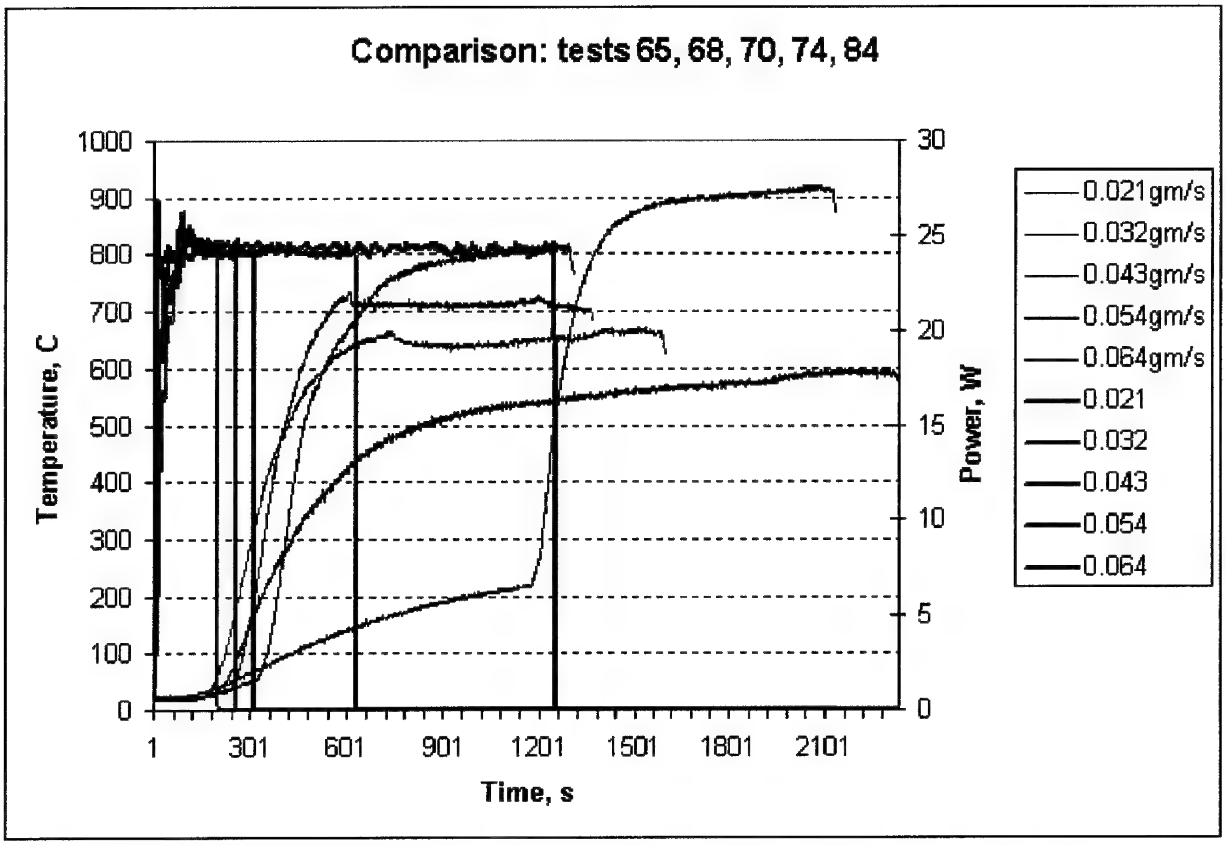


Fig. 27: Exhaust gas flow temperature of decomposition reaction products and electric power input as a function time.

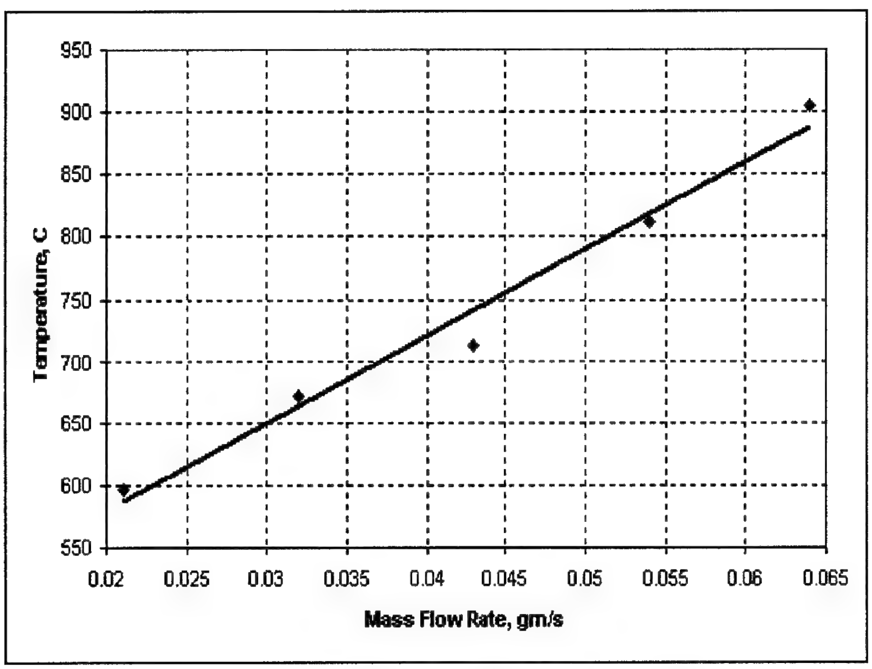


Fig. 28: Exhaust gas flow temperature of decomposition reaction products as a function of nitrous oxide mass flow rate. (tests 65, 68, 70, 74, 84)

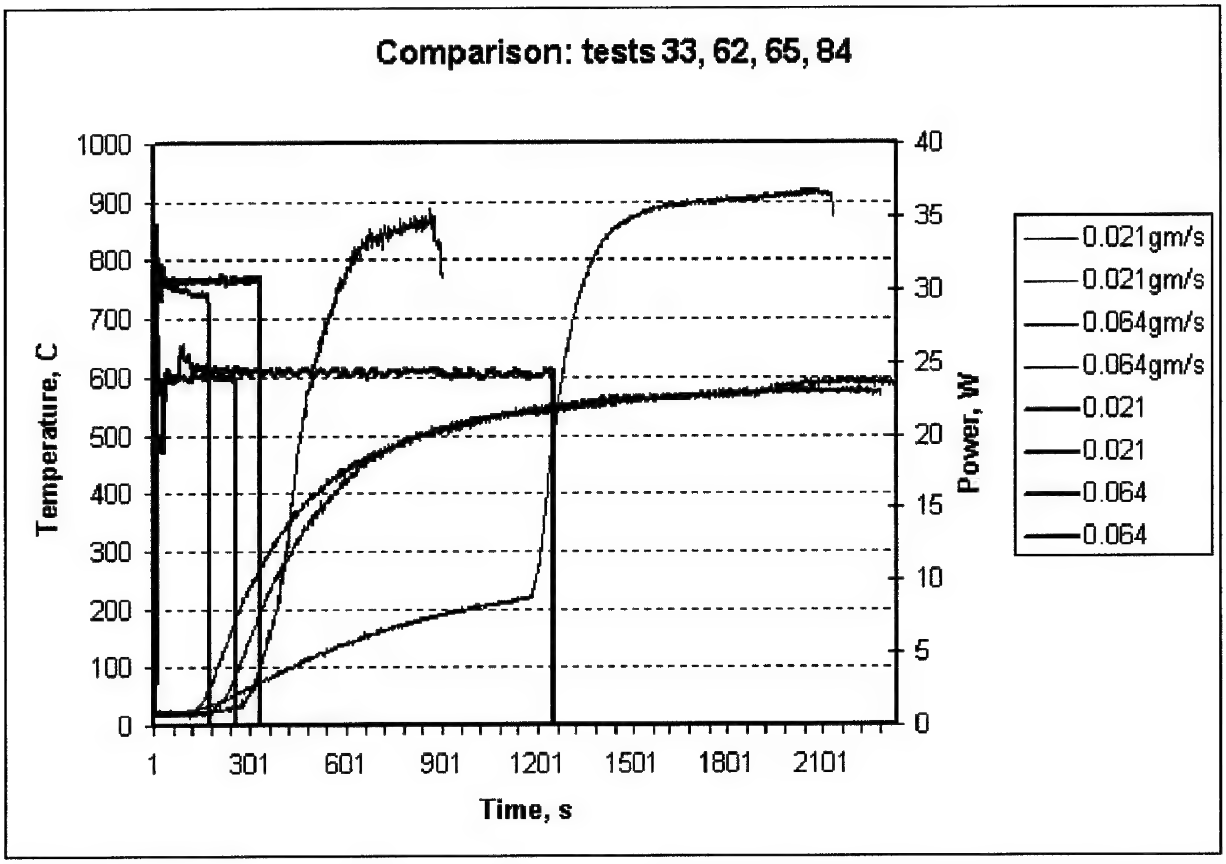


Fig. 29: Time-functions of exhaust gas flow and electric power input for 2 different mass flow rates.

Input Power for Nitrous Oxide Decomposition

Although, as it was shown in the previous section, the value of decomposition temperature at steady-state is practically unaffected by input power, its transient value (and, thus, start-up time) depends on power input. In fig. 30 higher power inputs correspond to steeper temperature rise during transient (and, thus, shorter start-up). The same is true for the case when input power is not enough to initiate decomposition reaction (tests 43 and 44). Overall, the transient temperature value is higher for higher power input. This relationship is not easy to quantify since during the test heating cycle overlaps with nitrous oxide flow injection. Therefore, although electric power input can be easy obtained in experiment, the amount of heat coming from nitrous oxide decomposition is unknown at present.

Since in orbit nitrous oxide flow rate change is expected to be a step function it is important to find out what electric energy input is required for the heater to support decomposition of certain flow. The heat input versus nitrous oxide mass flow rate was mapped for a test design (see fig.31). The lower range of nitrous oxide mass flow rate is determined by accuracy of the flow-meter. The upper range has been arbitrary selected by concerns regarding not melting an existing heater. The results were obtained by the following way. Starting from ambient temperature every time electric power was put into a heater for each certain pre-assigned flow rate. Starting each new test heat input was changed up or down with accuracy from 500 to 2000 J. When decomposition reaction was extinguished by nitrous oxide flow then additional power increment was added in the next test. Test was repeated until input heat was enough to support the flow. In the case when flow was supporting the reaction from beginning, the

power increment was subtracted for each next test until heat input could not support the flow. Heat input value was available by real time integration of power reading.

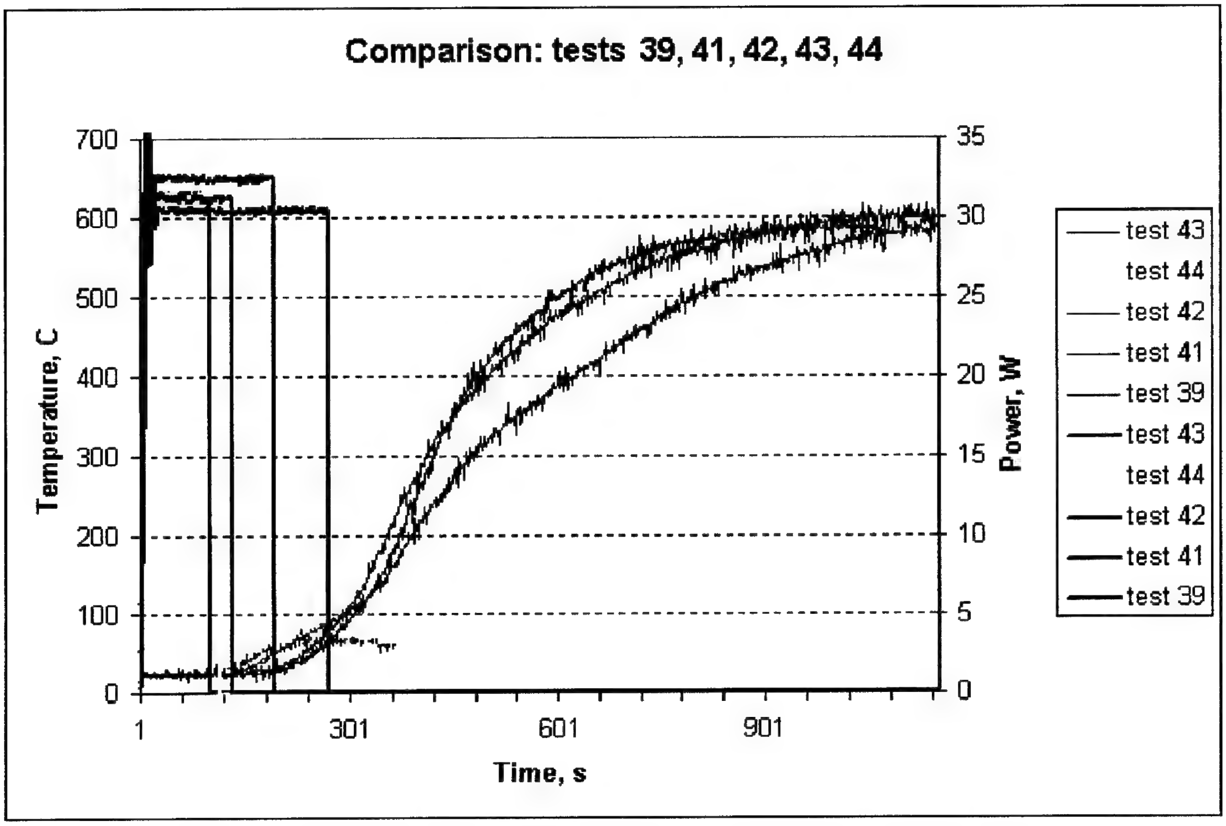


Fig. 30: Transient value of decomposition temperature vs. power input.

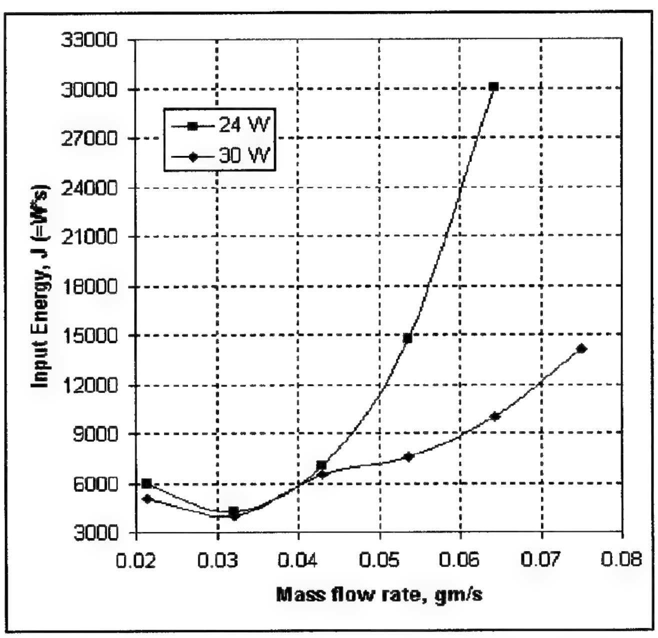


Fig. 31: Input power for nitrous oxide decomposition. (tests: 33, 42, 46, 49, 52, 62, 65, 68, 70, 74, 84)

Ideally (no heat losses) power input must be directly proportional to supported mass flow rates. The results, however, reveal that in fact a certain flow corresponds to the minimum heat input. Above and below this flow value extra heating is required to support the decomposition reaction inside the decomposer. Extra heating of flows lower than the optimal one is required, perhaps, to compensate for heat losses out of the decomposer since heat generation by nitrous oxide decomposition is lower. At flows higher than optimal one extra heating is required to decompose higher nitrous oxide mass flow rates. Again, due to heat losses this rise is non-linear.

The curve mapping exercise was repeated for two different heat input rates (24 and 30W). The results show that the rate of heat input is important for decomposition reaction initiation. The longer it takes to input the same amount of heat into the decomposer, the more heating is needed due to heat losses.

As this observation is dependant on the heat balance, the optimum mass flow rate may vary using a flight standard thruster under vacuum conditions. Hence further investigation is required with flight representative conditions.

6.4 Summary of Experimental Results

The potential for the nitrous oxide catalytic decomposition technique has been demonstrated in over than 100 of experimental tests at *Surrey Space Centre,* U.K. (see fig. 32).

Fig. 32: Self-sustaining nitrous oxide decomposition on *LCH 212* hydrazine catalyst. The electric leads have been disconnected from power supply after "ignition". No electric power is applied.

During these tests:

- The proof-of-concept was demonstrated.
- Repeatable, self-sustaining, decomposition of nitrous oxide has been achieved using different catalysts.
- Self-sustaining nitrous oxide decomposition was controlled by flow rate.
- Minimum input power required for nitrous oxide decomposition initiation is determined for specific design and two different power levels.
- Hot restarts at zero-power input have been repeatedly shown in operation.
- More than 50 different catalysts have been tested.
- A catalyst activation temperature as low as 250°C has been recorded.
- Nitrous oxide mass flow rates above 1.1gm/s have been supported.
- Decomposition temperatures in excess of 1500°C have been demonstrated.
- Electrical power input as low as 24W has been used.
- The time required to heat the catalyst from ambient to activation temperature has been as short as 3min.
- A catalyst lifetime in excess of 76min. was demonstrated.
- Nitrous oxide decomposition was shown to ignite solid fuel (PMMA). A vortex flow "pancake" hybrid rocket motor was successfully ignited by injection of hot gaseous products of the nitrous oxide decomposition into the combustion chamber (see fig. 33). [Haag 00] In the test, a well-known hydrazine decomposition catalyst (*Shell 405*) was used to decompose nitrous oxide. No additional ignition system was needed.

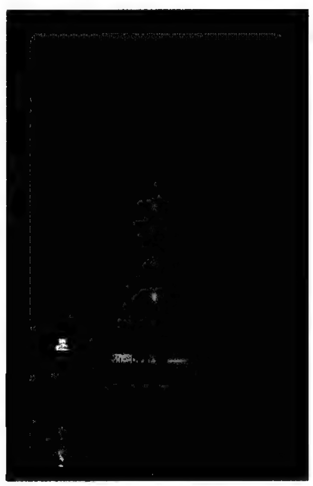


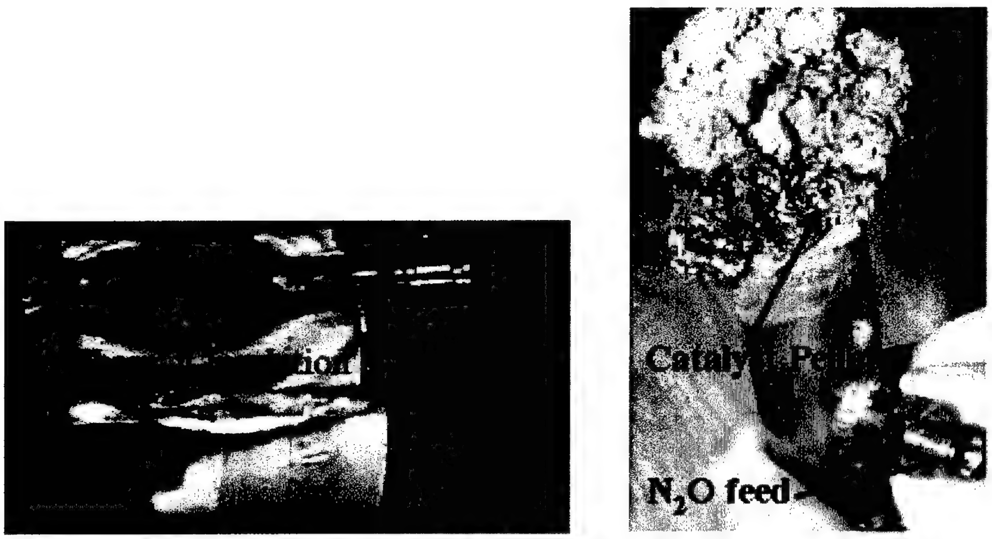
Fig. 33: A vortex flow "pancake" hybrid rocket motor firing.

Despite these achievements, two major challenges were revealed. Both of them are associated with choice of high temperature materials.

The first challenge is due to high temperature generated inside decomposition chamber. This temperature is enough to melt stainless steel casing (see fig. 34). Application of refractory materials in the design is presently not considered because they are difficult to manufacture and expensive. Lowering the process temperature is unfavourable because it sacrifices thruster performance. Application of alumina ceramics was found promising for high temperature casing design. However, additional tests comprising both thermal and mechanical stress loads need to be carried out before the

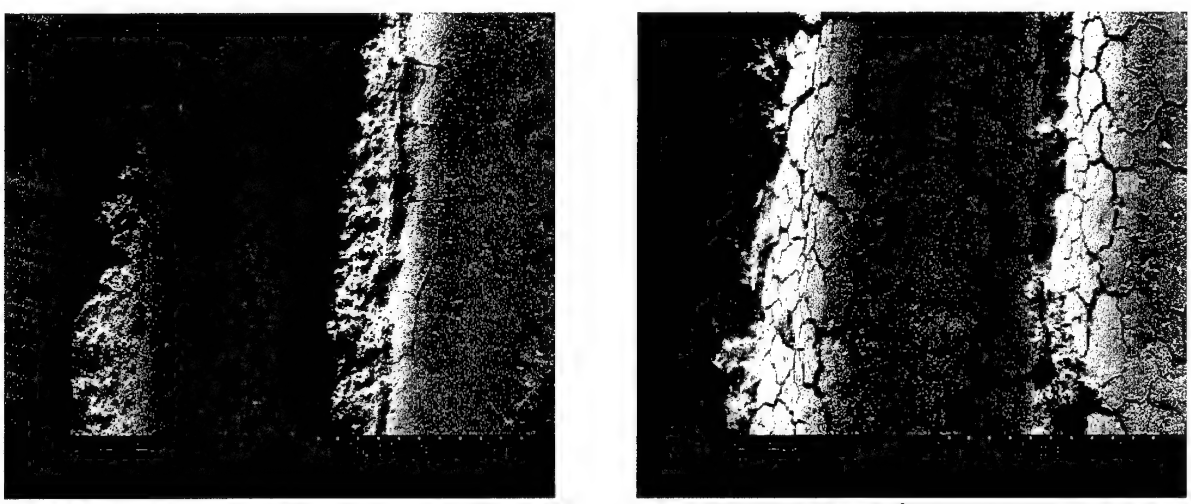
final conclusion can be made. The future designs involving ceramics will require careful consideration of thermal expansion coefficients.

The second challenge is associated with high temperature (>1100°C) instability of the catalyst materials. The literature search on nitrous oxide decomposition catalysts provided no answer for the problem. Since practical applications for nitrous oxide decomposition catalysts are currently limited to environmental outlooks rather than power generation the maximum explored temperatures did not exceed 800°C. It is also believed that above this temperature homogeneous (or thermal) decomposition dominates the process. However, it was found that in the case of suggested dynamic system homogeneous decomposition rates at 800°C are not high enough to initiate self-sustaining decomposition; therefore, the need in high temperature catalyst still remains.



a b

Fig. 34: Test design after firing: a) Stainless steel pipe is melted with iron catalyst and *MICROPORE* thermal insulation; b) Alumina pellets coated by catalyst have survived the heat.



a b

Fig. 35: Monolith surface a) before (virgin); and b) after (eroded) test.

Meanwhile, it was found that above 1100°C the following problems occur:

- Zeolites and silica sinter
- Cordierite matrix does not withstand the temperature (see fig. 35)
- Iridium and rhodium oxides sublimate
- Nickel, cobalt and iron react with alumina or magnesia substrates forming spinels (complex oxides).

The work on high temperature stable catalysts continues.

7. PROVISIONAL DESIGN FOR FLIGHT THRUSTER

Based on obtained experience in nitrous oxide decomposition the following parameters for future flight thruster are expected:
Thrust = 0.1 – 0.2 N
Mass flow rates of nitrous oxide = 0.10 – 0.15 gm/s.
Catalyst loading 5-7 gm
Catalyst Bed size:
length = 40-50 mm
∅15-20mm (inner)
Power.required for N2O decomposition initiation = 24W applied for 5-7 min.
Thermal Insulation = 25mm Micropore.
The exhaust temperatures = 900-1000°C.

8. EXECUTIVE SUMMARY

Nitrous oxide has been identified at Surrey Space Centre as a rocket propellant for small satellites. Application of this propellant on small spacecraft is advantageous because:

- All propulsion functions for small satellites can be covered.
- Multi-mode propulsion system can be designed for a small satellite. Such a system will have lower total dry mass fraction and increase the number of mission scenarios due to more efficient propellant management.
- It has potential in providing significant reduction of propulsion system cost.

Previous research regarding nitrous oxide space application proved that:

- It can be stored in orbit.
- It can be used as a resistojet propellant.
- Its self-sustaining decomposition is attainable.

A continuation of earlier efforts, nitrous oxide catalytic decomposition is a focus of current research at Surrey. It is considered to be a key-technique for a novel monopropellant thruster concept. This technique reduces input power requirements for power-constrained small satellites in comparison with a thermal decomposition technique, and, therefore, will be affordable for smaller spacecraft. As a further step, nitrous oxide catalytic decomposition technique is suggested for bipropellant thruster ignition.
As a first approach towards the monopropellant thruster a catalytic decomposer for nitrous oxide has been designed and successfully tested along with supporting infrastructure.

Catalysts for nitrous oxide decomposition exist. They have been proven feasible for heat and thrust generation as well as hybrid rocket motor ignition.
Although the existing catalysts work well, high-temperature stable catalyst materials would further enhance the performance of a monopropellant thruster.
Current research at Surrey is focused on the investigation of the performance of a nitrous oxide catalytic decomposer leading towards the development of a nitrous oxide monopropellant thruster.
In particular, it has been found that:

- The final (steady-state) exhaust gas flow temperature of decomposition reaction products for each particular design is a function of nitrous oxide mass flow rate only.
- Transient value of exhaust gas flow temperature depends on power input.

The ultimate research goal is to provide theoretical and experimental basis for the development of the first nitrous oxide multi-mode propulsion system for small satellite applications.

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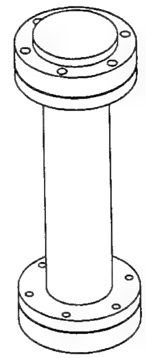
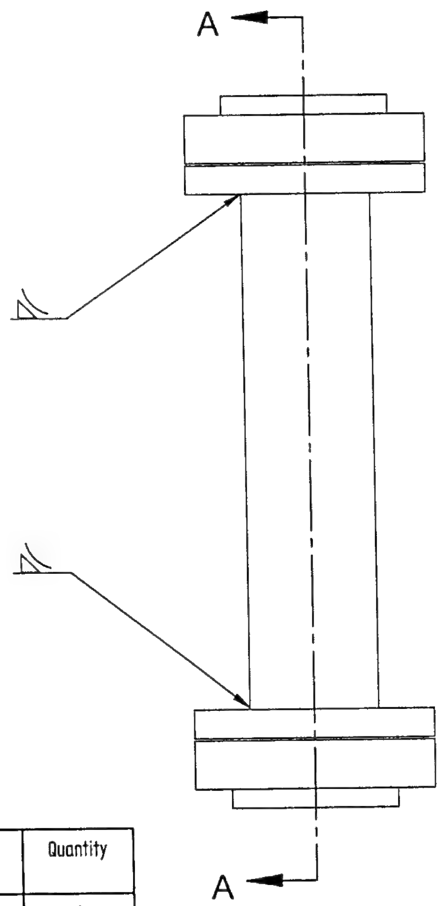
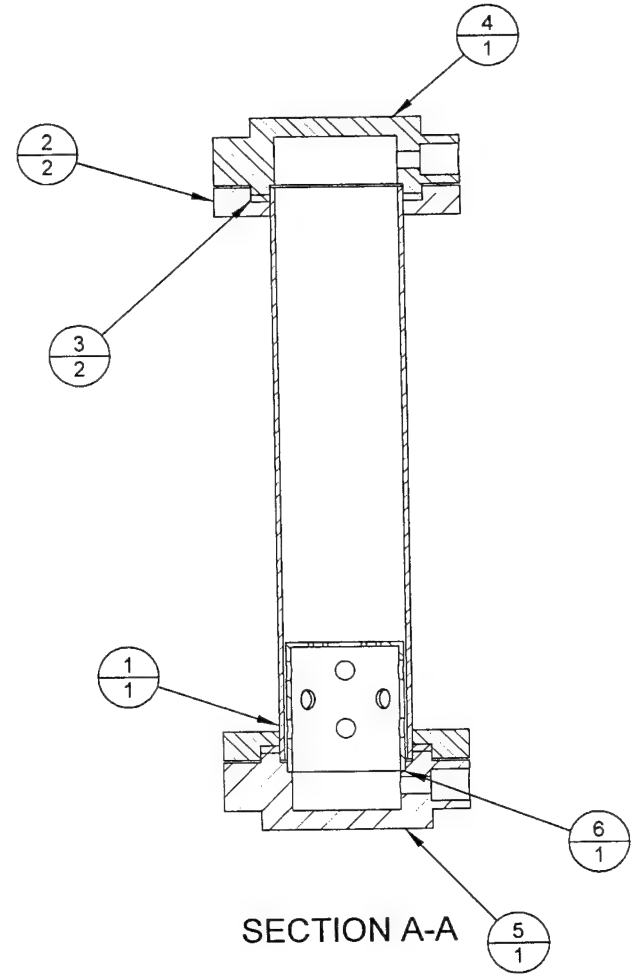
APPENDIX A

Design #4 drawings

REV	DESCRIPTION	ECN NO.	DATE
1	RELEASE		20-JUL-2000







SECTION A-A

Item Number	Document Number	Title	Material	Quantity
1	Chamber.par	CHAMBER	Stainless Steel	1
2	Chamber Ends.par	CHAMBER ENDS	Stainless Steel	2
3	Washer.par	WASHER	Copper	2
4	Nozzle End.par	NOZZLE END	Stainless Steel	1
5	Chamber Base.par	CHAMBER BASE	Stainless Steel	1
6	Spacer.par	SPACER	Stainless Steel	1

THIRD ANGLE PROJECTION

DO NOT SCALE
IF IN DOUBT ASK!

UNLESS OTHERWISE SPECIFIED

GENERAL TOLERANCES
DECIMAL ANGULAR
.X +/-0.20 +/-0.50
.XX +/-0.10
.XXX +/-0.05

1. ALL DIMENSIONS IN MILLIMETERS
2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5
3. ALL UNSPECIFIED RADII R2.5
4. REMOVE SWARF FROM ALL HOLES

SURREY
SATELLITE TECHNOLOGY LTD
SURREY SPACE CENTRE, GUILDFORD GU2 5XH
TEL: 01483 259278 FAX: 01483 259503

TITLE: DECOMPOSER ASSEMBLY

DRAWN: P JOLLEY — DATE: 20-JUL-2000
APPROVED: — DATE:

SCALE: 1 : 1
SHEET: 1 of 1
STOCK NUMBER: ITM/XXXX###
REVISION: 1

A3 - VER 1.5

REVISIONS			
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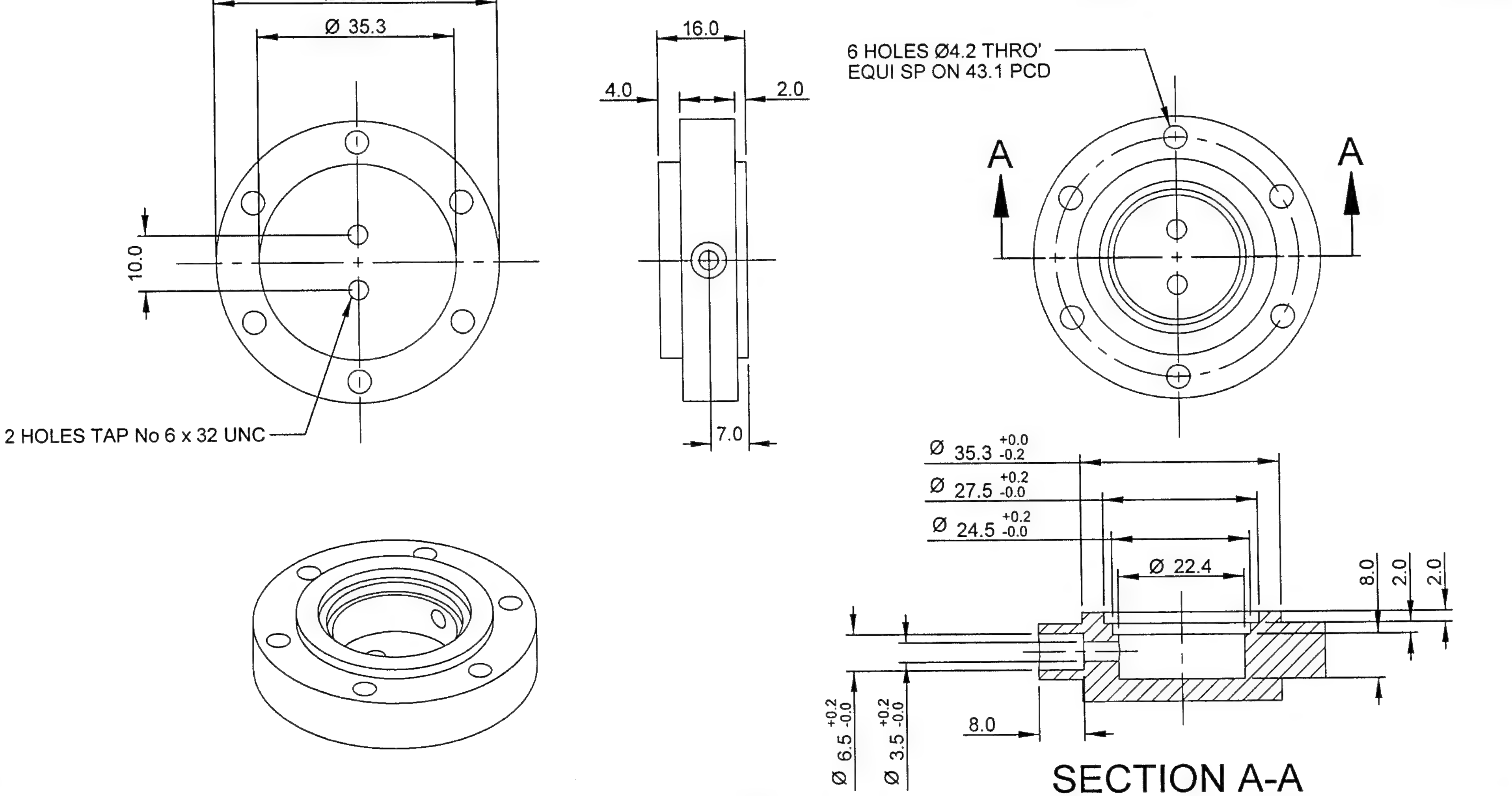

MATERIAL
Stainless steel

FINISH
SURFACE FINISH N7 (DO NOT VIBRO)

THIRD ANGLE PROJECTION

DO NOT SCALE
IF IN DOUBT ASK!

UNLESS OTHERWISE SPECIFIED

GENERAL TOLERANCES
DECIMAL .X +/-0.20 .XX +/-0.10 .XXX +/-0.05
ANGULAR +/-0.50

1. ALL DIMENSIONS IN MILLIMETERS
2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5
3. ALL UNSPECIFIED RADII R2.5
4. REMOVE SWARF FROM ALL HOLES

SURREY
SATELLITE TECHNOLOGY LTD

SURREY SPACE CENTRE, GUILDFORD GU2 5XH
TEL: 01483 259278 FAX: 01483 259503

TITLE
CHAMBER BASE

DRAWN: P JOLLEY
DATE: 19-JUL-2000
APPROVED:
DATE:

SCALE: 1 : 1
SHEET: 1 of 1
STOCK NUMBER: ITM/XXXX###
REVISION: 1

A4 -VER 1.5

REVISIONS			
REV	DESCRIPTION	ECN NO.	DATE
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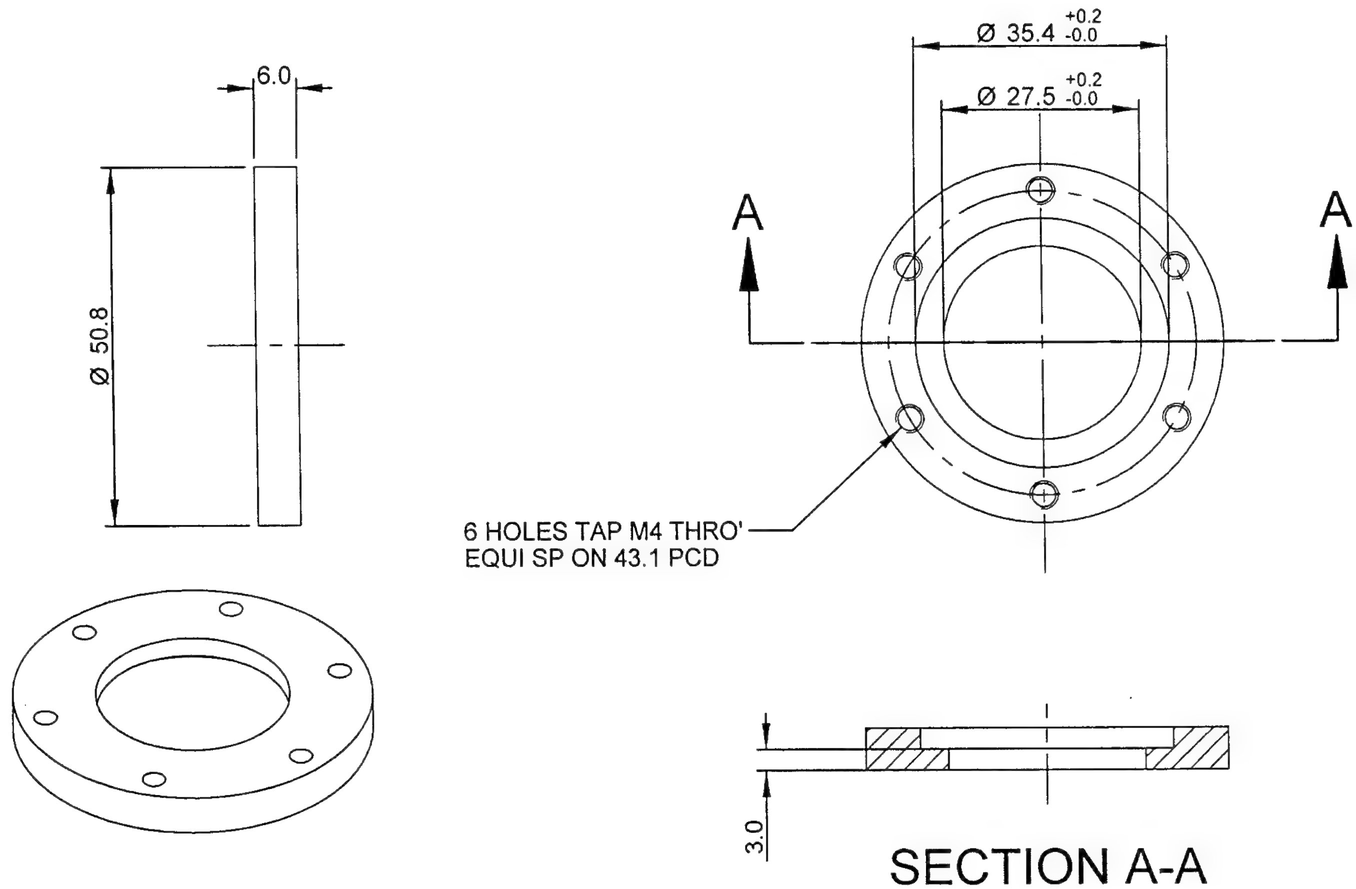

Make 2, One for either end of the chamber

MATERIAL Stainless Steel	THIRD ANGLE PROJECTION DO NOT SCALE IF IN DOUBT ASK!	SURREY SATELLITE TECHNOLOGY LTD SURREY SPACE CENTRE, GUILDFORD GU2 5XH TEL: 01483 259278 FAX: 01483 259503	TITLE CHAMBER ENDS	DRAWN P JOLLEY APPROVED	DATE 20-JUL-2000 DATE
FINISH SURFACE FINISH N7 (DO NOT VIBRO)	UNLESS OTHERWISE SPECIFIED GENERAL TOLERANCES DECIMAL .X +/-0.20 .XX +/-0.10 .XXX +/-0.05 ANGULAR +/-0.50 1. ALL DIMENSIONS IN MILLIMETERS 2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5 3. ALL UNSPECIFIED RADII R2.5 4. REMOVE SWARF FROM ALL HOLES	ALL INFORMATION CONTAINED IN THIS DOCUMENT IS PROPRIETARY AND CONFIDENTIAL TO SURREY SATELLITE TECHNOLOGY LTD ("SSTL") AND IS NOT TO BE REPRODUCED, IN WHOLE OR IN PART, OR USED FOR ANY PURPOSES OTHER THAN FOR WHICH IT IS PROVIDED EXCEPT ON "SSTL" ORDER OR "SSTL" PRIOR WRITTEN CONSENT.	SCALE 1 : 1 SHEET 1 of 1	STOCK NUMBER ITM/XXXX###	REVISION 1

A4 -VER 1.5

REVISIONS			
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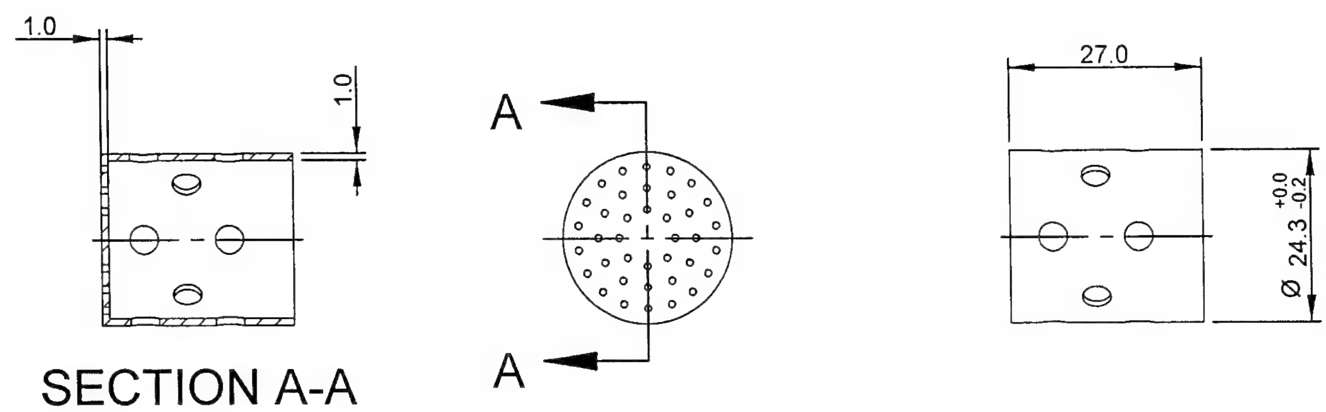

MATERIAL SS 316L	THIRD ANGLE PROJECTION DO NOT SCALE IF IN DOUBT ASK!	SURREY SATELLITE TECHNOLOGY LTD SURREY SPACE CENTRE, GUILDFORD GU2 5XH TEL: 01483 259278 FAX: 01483 259503	TITLE SPACER	DRAWN P JOLLEY DATE 28-JUN-2000 APPROVED DATE
FINISH SURFACE FINISH N7 (DO NOT VIBRO)	UNLESS OTHERWISE SPECIFIED GENERAL TOLERANCES DECIMAL .X +/-0.20 .XX +/-0.10 .XXX +/-0.05 ANGULAR +/-0.50 1. ALL DIMENSIONS IN MILLIMETERS 2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5 3. ALL UNSPECIFIED RADII R2.5 4. REMOVE SWARF FROM ALL HOLES	ALL INFORMATION CONTAINED IN THIS DOCUMENT IS PROPRIETARY AND CONFIDENTIAL TO SURREY SATELLITE TECHNOLOGY LTD ("SSTL") AND IS NOT TO BE REPRODUCED, IN WHOLE OR IN PART, OR USED FOR ANY PURPOSES OTHER THAN FOR WHICH IT IS PROVIDED EXCEPT ON "SSTL" ORDER OR "SSTL" PRIOR WRITTEN CONSENT.	SCALE 1 : 1 SHEET 1 of 1	STOCK NUMBER ITM/XXXX### REVISION 1

A4 -VER 1.5

REVISIONS

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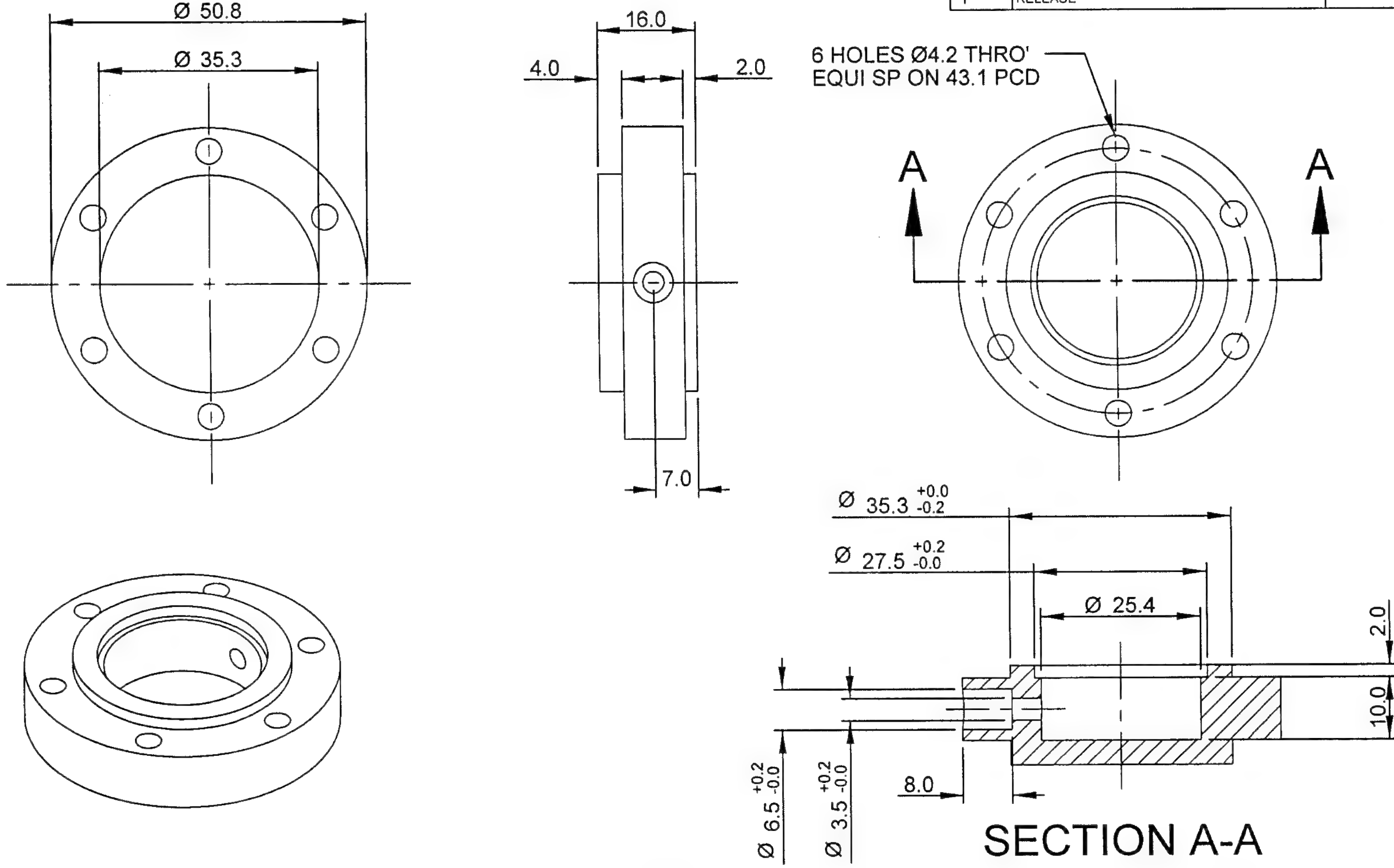

MATERIAL Stainless Steel	THIRD ANGLE PROJECTION DO NOT SCALE IF IN DOUBT ASK!	SURREY SATELLITE TECHNOLOGY LTD SURREY SPACE CENTRE, GUILDFORD GU2 5XH TEL: 01483 259278 FAX: 01483 259503	TITLE NOZZLE END	DRAWN P JOLLEY DATE 19-JUL-2000 APPROVED DATE
FINISH SURFACE FINISH N7 (DO NOT VIBRO)	UNLESS OTHERWISE SPECIFIED GENERAL TOLERANCES DECIMAL .X +/-0.20 .XX +/-0.10 .XXX +/-0.05 ANGULAR +/-0.50 1. ALL DIMENSIONS IN MILLIMETERS 2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5 3. ALL UNSPECIFIED RADII R2.5 4. REMOVE SWARF FROM ALL HOLES	ALL INFORMATION CONTAINED IN THIS DOCUMENT IS PROPRIETARY AND CONFIDENTIAL TO SURREY SATELLITE TECHNOLOGY LTD ("SSTL") AND IS NOT TO BE REPRODUCED, IN WHOLE OR IN PART, OR USED FOR ANY PURPOSES OTHER THAN FOR WHICH IT IS PROVIDED EXCEPT ON "SSTL" ORDER OR "SSTL" PRIOR WRITTEN CONSENT.	SCALE 1 : 1 SHEET 1 of 1	STOCK NUMBER ITM/XXXX### REVISION 1

A4 -VER 1.5

REVISIONS			
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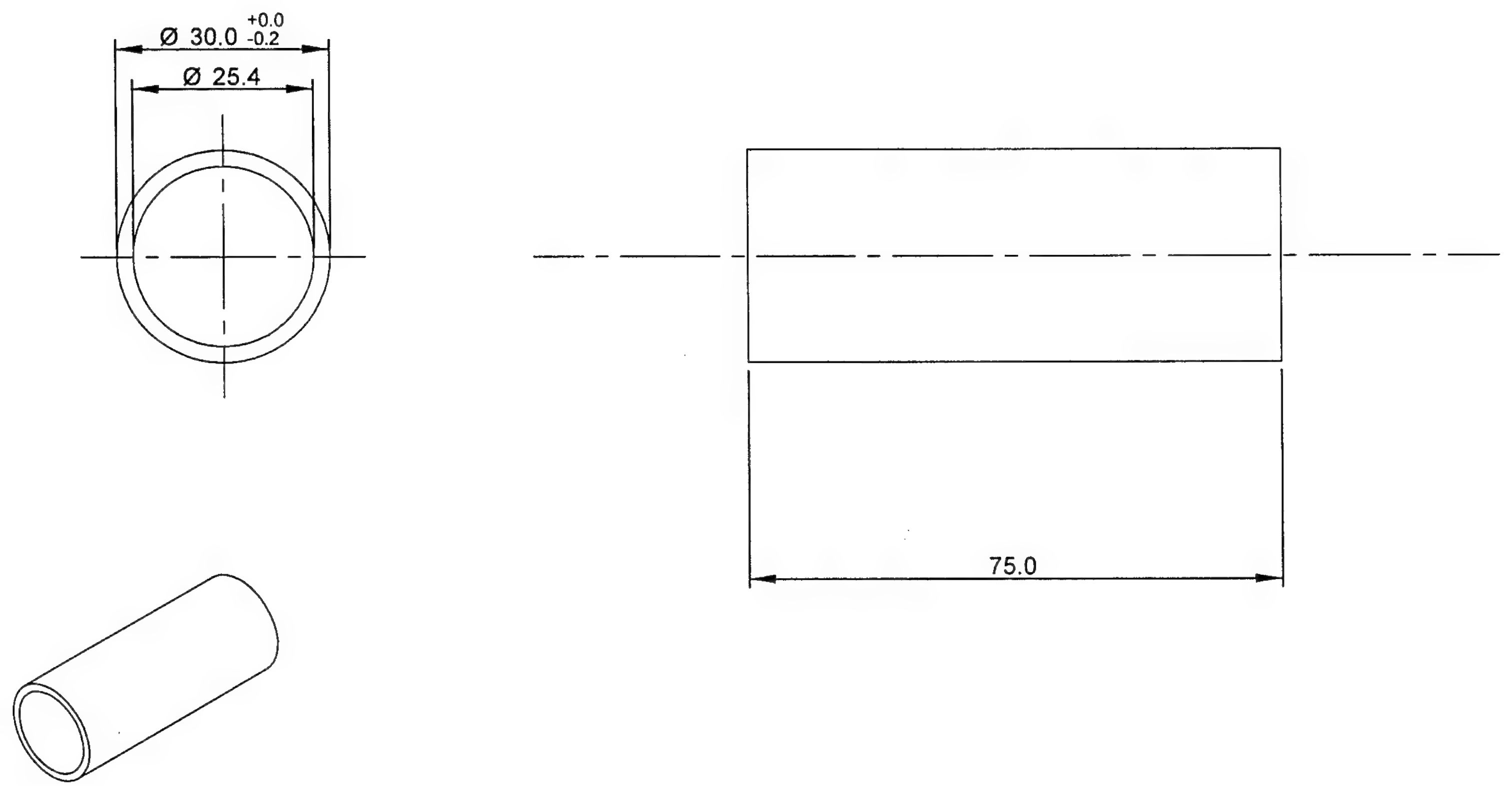

MATERIAL Stainless Steel	THIRD ANGLE PROJECTION DO NOT SCALE IF IN DOUBT ASK!	SURREY SATELLITE TECHNOLOGY LTD	TITLE CHAMBER	DRAWN P JOLLEY APPROVED	DATE 20-JUL-2000 DATE
FINISH SURFACE FINISH N7 (DO NOT VIBRO)	UNLESS OTHERWISE SPECIFIED GENERAL TOLERANCES DECIMAL .X +/-0.20 .XX +/-0.10 .XXX +/-0.05 ANGULAR +/-0.50 1. ALL DIMENSIONS IN MILLIMETERS 2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5 3. ALL UNSPECIFIED RADII R2.5 4. REMOVE SWARF FROM ALL HOLES	SURREY SPACE CENTRE, GUILDFORD GU2 5XH TEL: 01483 259278 FAX: 01483 259503 ALL INFORMATION CONTAINED IN THIS DOCUMENT IS PROPRIETARY AND CONFIDENTIAL TO SURREY SATELLITE TECHNOLOGY LTD ("SSTL") AND IS NOT TO BE REPRODUCED, IN WHOLE OR IN PART, OR USED FOR ANY PURPOSES OTHER THAN FOR WHICH IT IS PROVIDED EXCEPT ON "SSTL" ORDER OR "SSTL" PRIOR WRITTEN CONSENT.	SCALE 1 : 1 SHEET 1 of 1	STOCK NUMBER ITM/XXXX###	REVISION 1

A4 -VER 1.5

REVISIONS			
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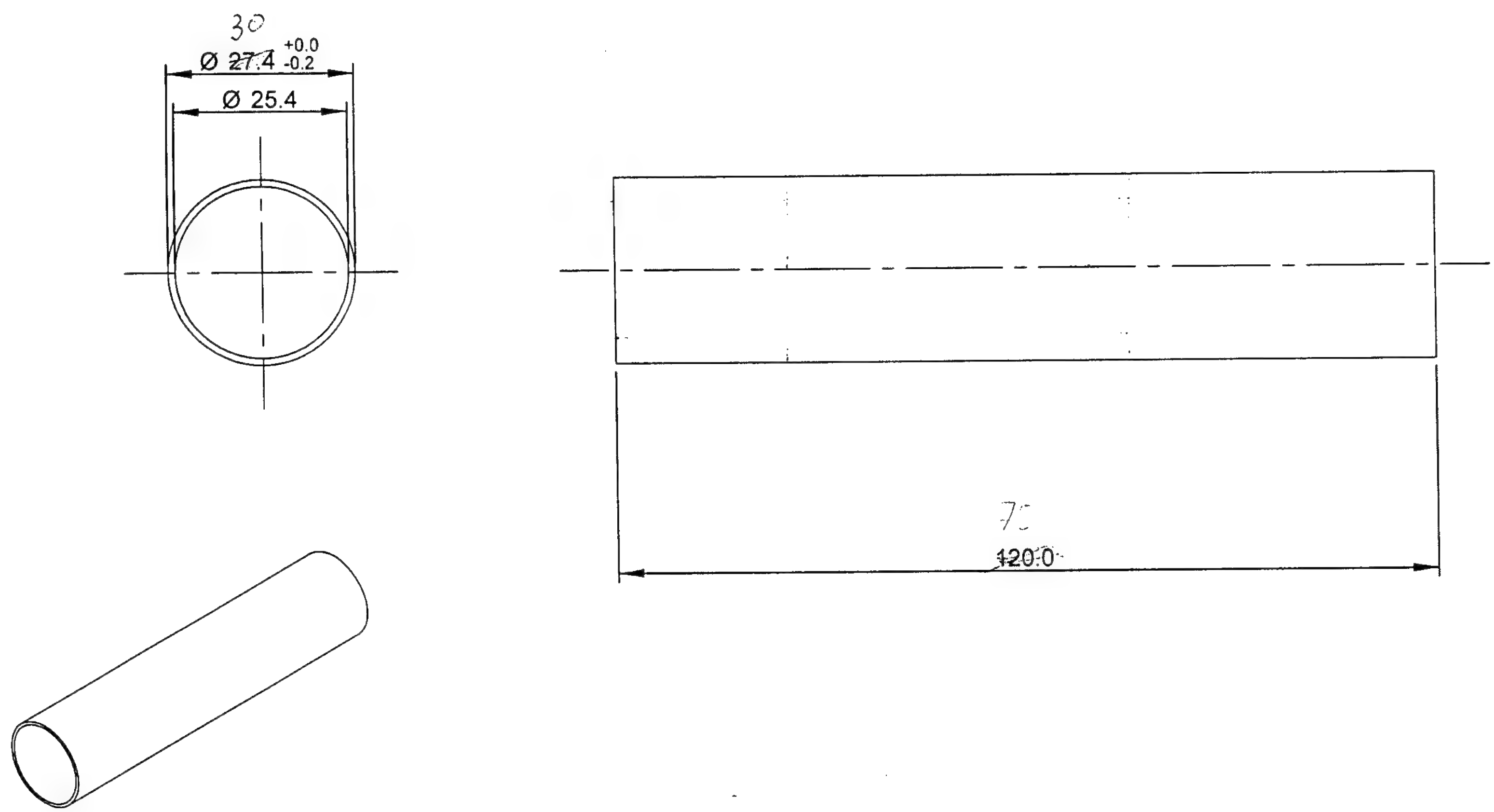
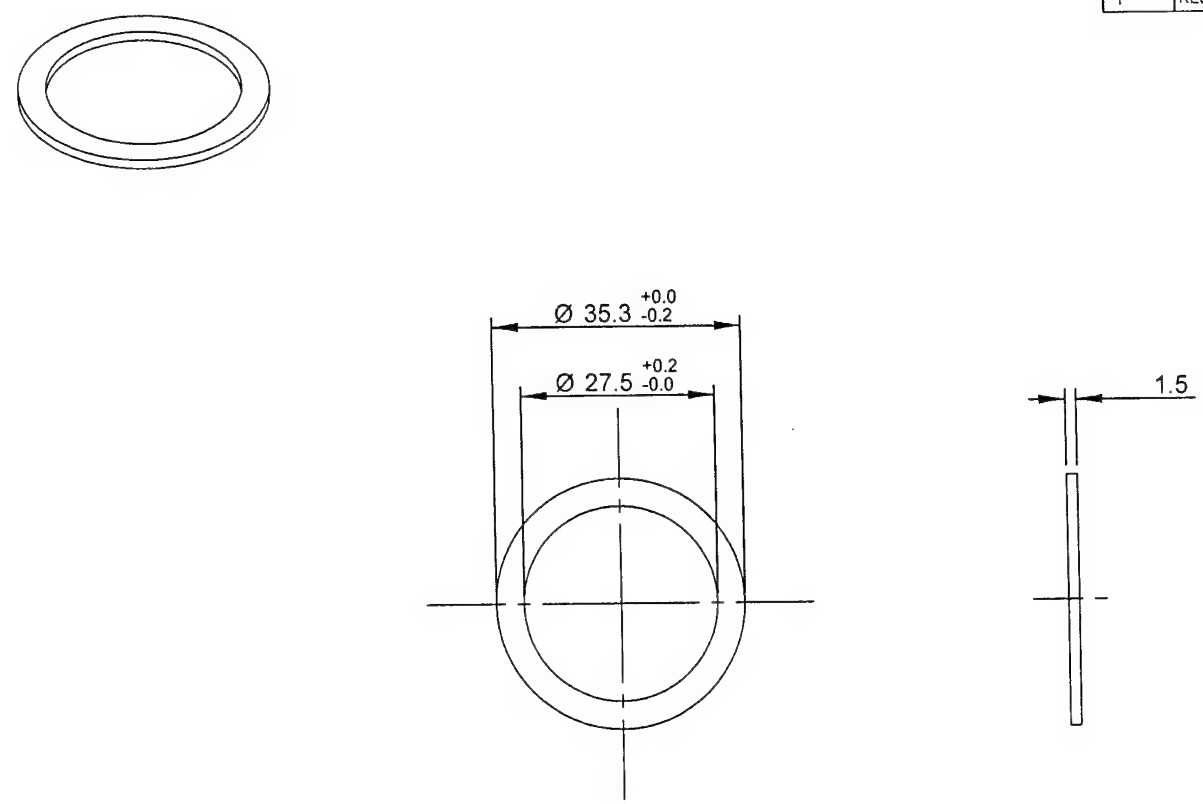


MATERIAL: Stainless Steel	THIRD ANGLE PROJECTION — DO NOT SCALE — IF IN DOUBT ASK!	SURREY SATELLITE TECHNOLOGY LTD	TITLE: CHAMBER		DRAWN: P JOLLEY	DATE: 20-JUL-2000
					APPROVED	DATE
FINISH: SURFACE FINISH N7 (DO NOT VIBRO)	UNLESS OTHERWISE SPECIFIED	SURREY SPACE CENTRE, GUILDFORD GU2 5XH TEL: 01483 259278 FAX: 01483 259503	SCALE: 1 : 1	STOCK NUMBER: ITM/XXXX####		REVISION: 1
	GENERAL TOLERANCES: DECIMAL .X +/-0.20, .XX +/-0.10, .XXX +/-0.05; ANGULAR +/-0.50 1. ALL DIMENSIONS IN MILLIMETERS 2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5 3. ALL UNSPECIFIED RADII R2.5 4. REMOVE SWARF FROM ALL HOLES	ALL INFORMATION CONTAINED IN THIS DOCUMENT IS PROPRIETARY AND CONFIDENTIAL TO SURREY SATELLITE TECHNOLOGY LTD ("SSTL") AND IS NOT TO BE REPRODUCED, IN WHOLE OR IN PART, OR USED FOR ANY PURPOSES OTHER THAN FOR WHICH IT IS PROVIDED EXCEPT ON "SSTL" ORDER OR "SSTL" PRIOR WRITTEN CONSENT.	SHEET: 1 of 1			

A4 -VER 1.5



REVISIONS

REV	DESCRIPTION	ECN NO.	DATE
1	RELEASE		20-JUL-2000

MATERIAL: Copper

FINISH: SURFACE FINISH N7 (DO NOT VIBRO)

THIRD ANGLE PROJECTION

DO NOT SCALE
IF IN DOUBT ASK!

UNLESS OTHERWISE SPECIFIED

GENERAL TOLERANCES
DECIMAL .X +/-0.20 .XX +/-0.10 .XXX +/-0.05
ANGULAR +/-0.50

1. ALL DIMENSIONS IN MILLIMETERS
2. BREAK ALL EDGES & EXTERNAL CORNERS BY 0.2 - 0.5
3. ALL UNSPECIFIED RADII R2.5
4. REMOVE SWARF FROM ALL HOLES

SURREY SATELLITE TECHNOLOGY LTD
SURREY SPACE CENTRE, GUILDFORD GU2 5XH
TEL: 01483 259278 FAX: 01483 259503

TITLE: WASHER

DRAWN: P JOLLEY — DATE: 20-JUL-2000

APPROVED: — DATE:

SCALE: 1 : 1

SHEET: 1 of 1

STOCK NUMBER: ITM/XXXX###

REVISION: 1

A4 -VER 1.5

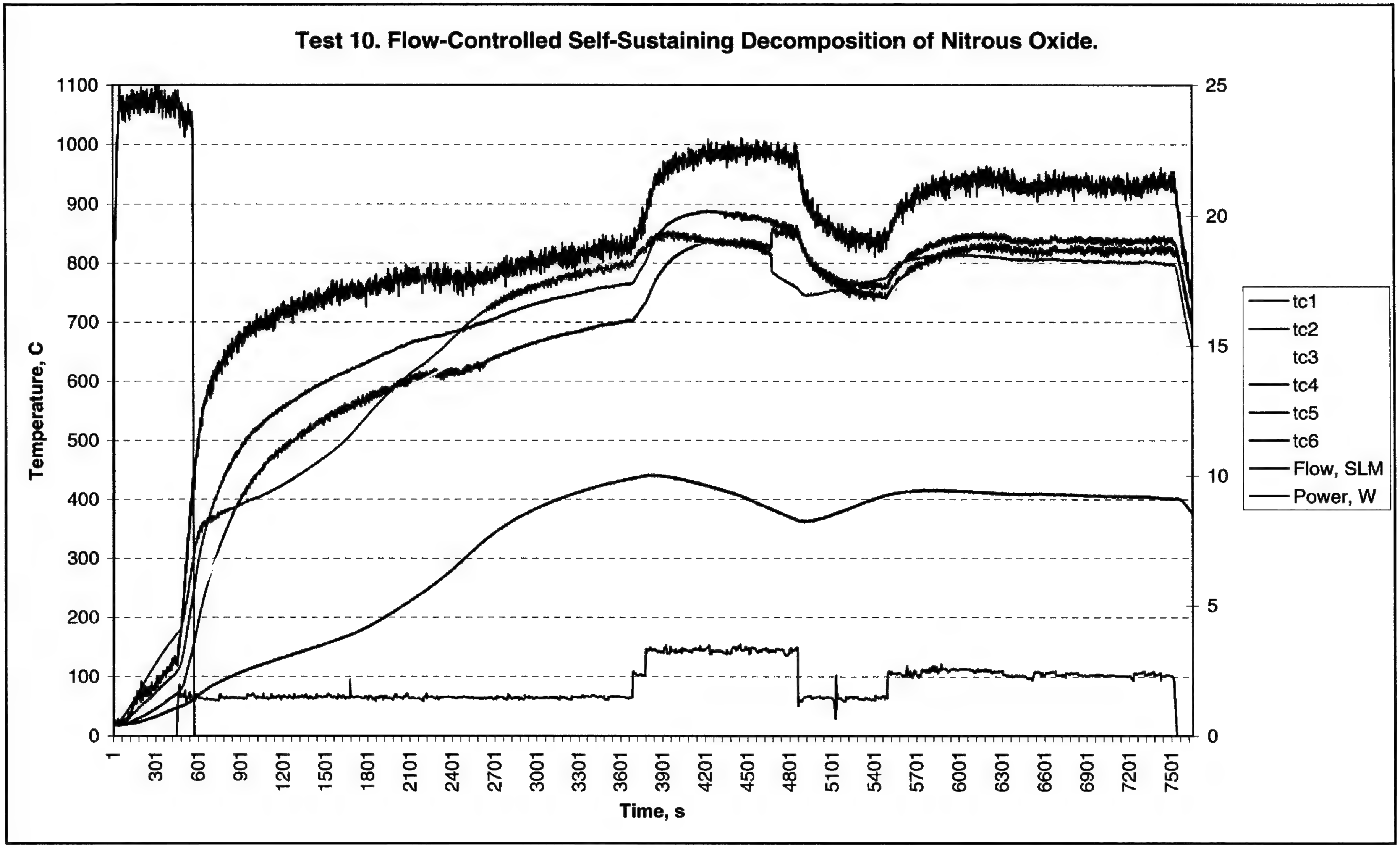
APPENDIX B

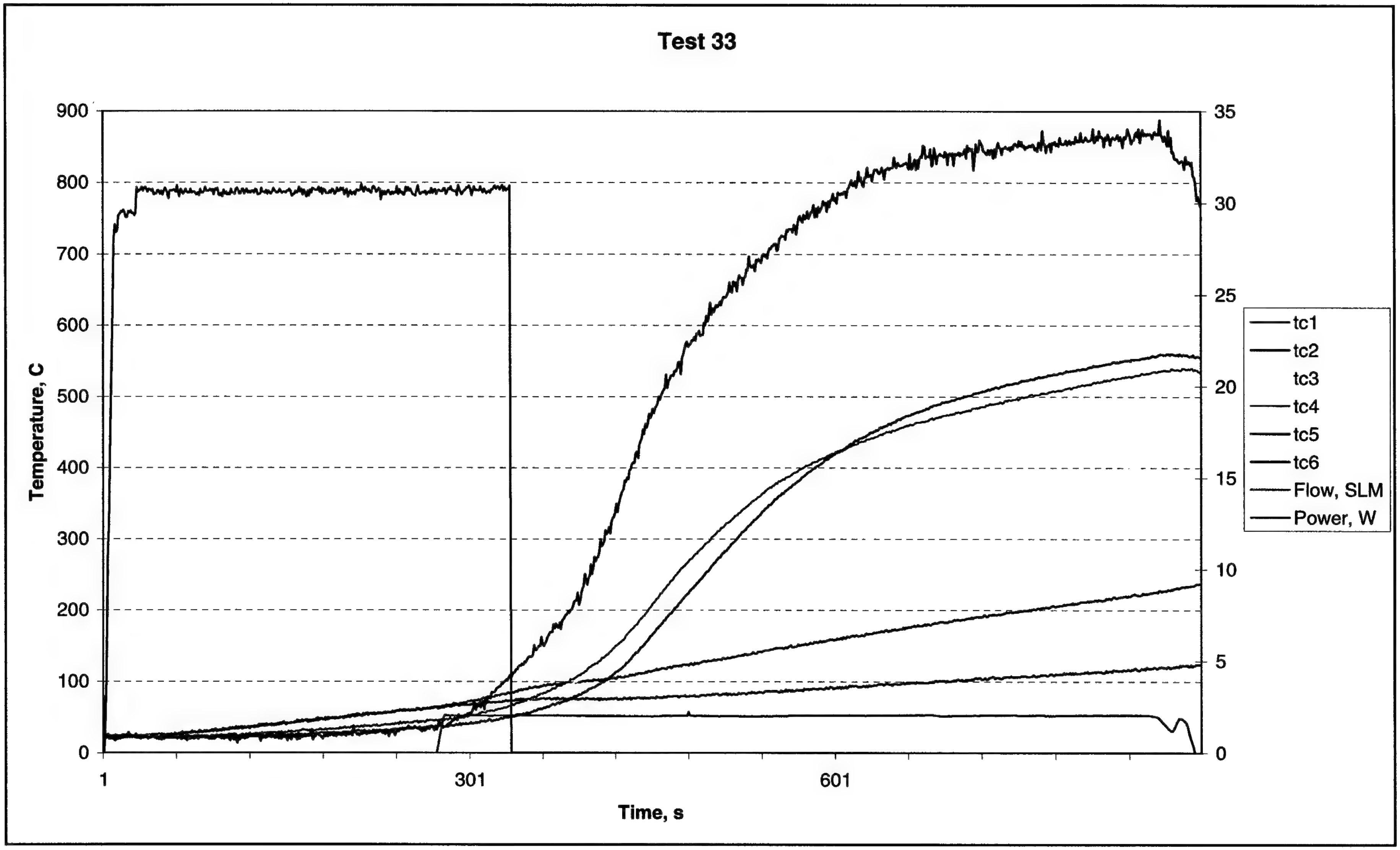
Test Results

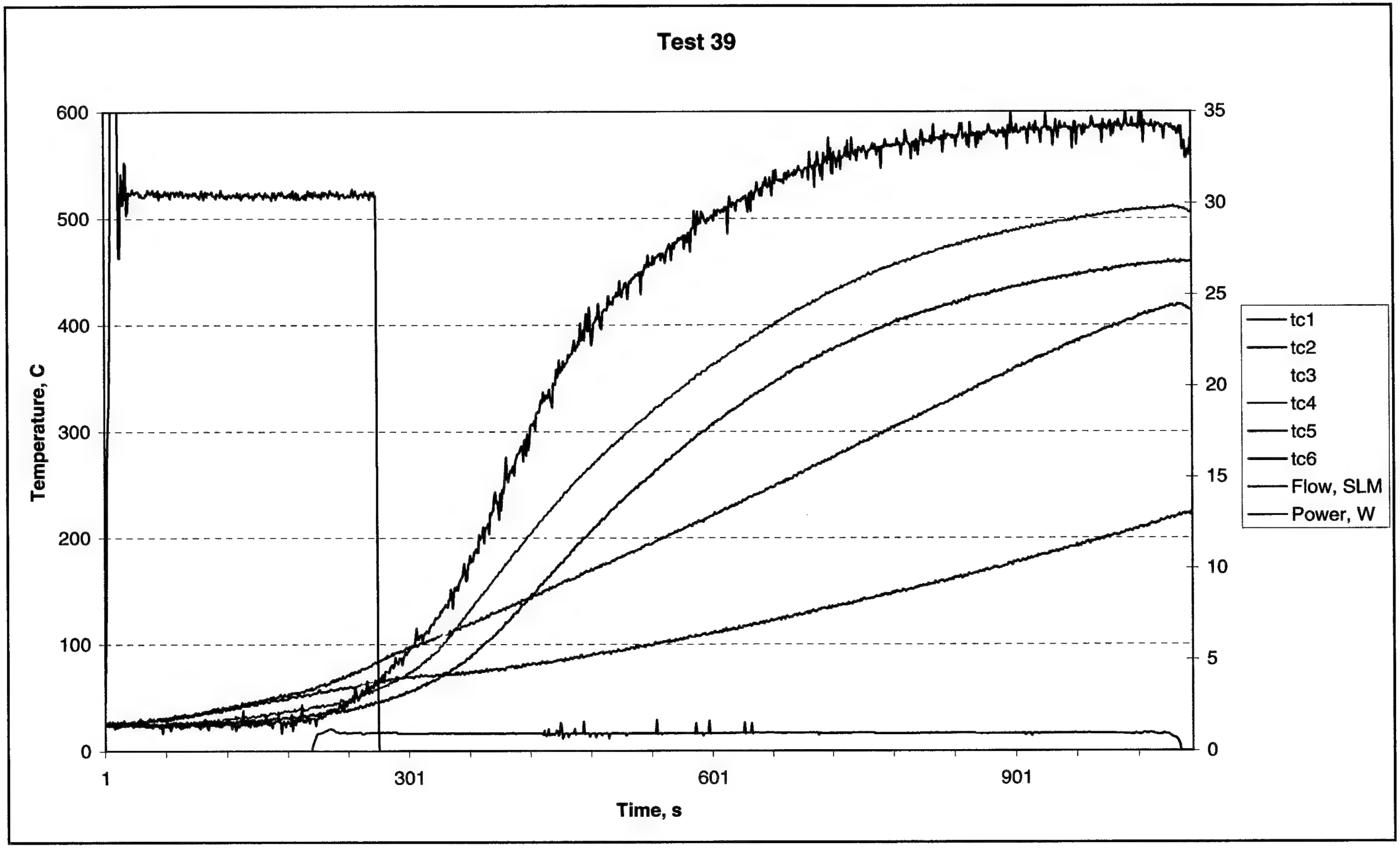
Test #	Flow	Mass Flow Rate	Average Power	Total Energy Input
	SLM	gm/s	W	J=W*s
10	0-3.28	0.000-0.099	24	13503
33	2.13	0.064	31	10026
39	0.98	0.029	30	8240
41	0.98	0.030	32	6001
42	1.07	0.032	31	4016
43	0.97	0.029	31	3011
44	0.99	0.030	32	3530
46	1.78	0.054	34	7556
49	2.49	0.075	34	14078
52	1.42	0.043	30	6533
62	0.71	0.021	30	5026
65	0.71	0.021	24	5964
68	1.07	0.032	24	4253
70	1.42	0.043	24	7074
74	1.78	0.054	24	14742
84	2.13	0.064	24	30058

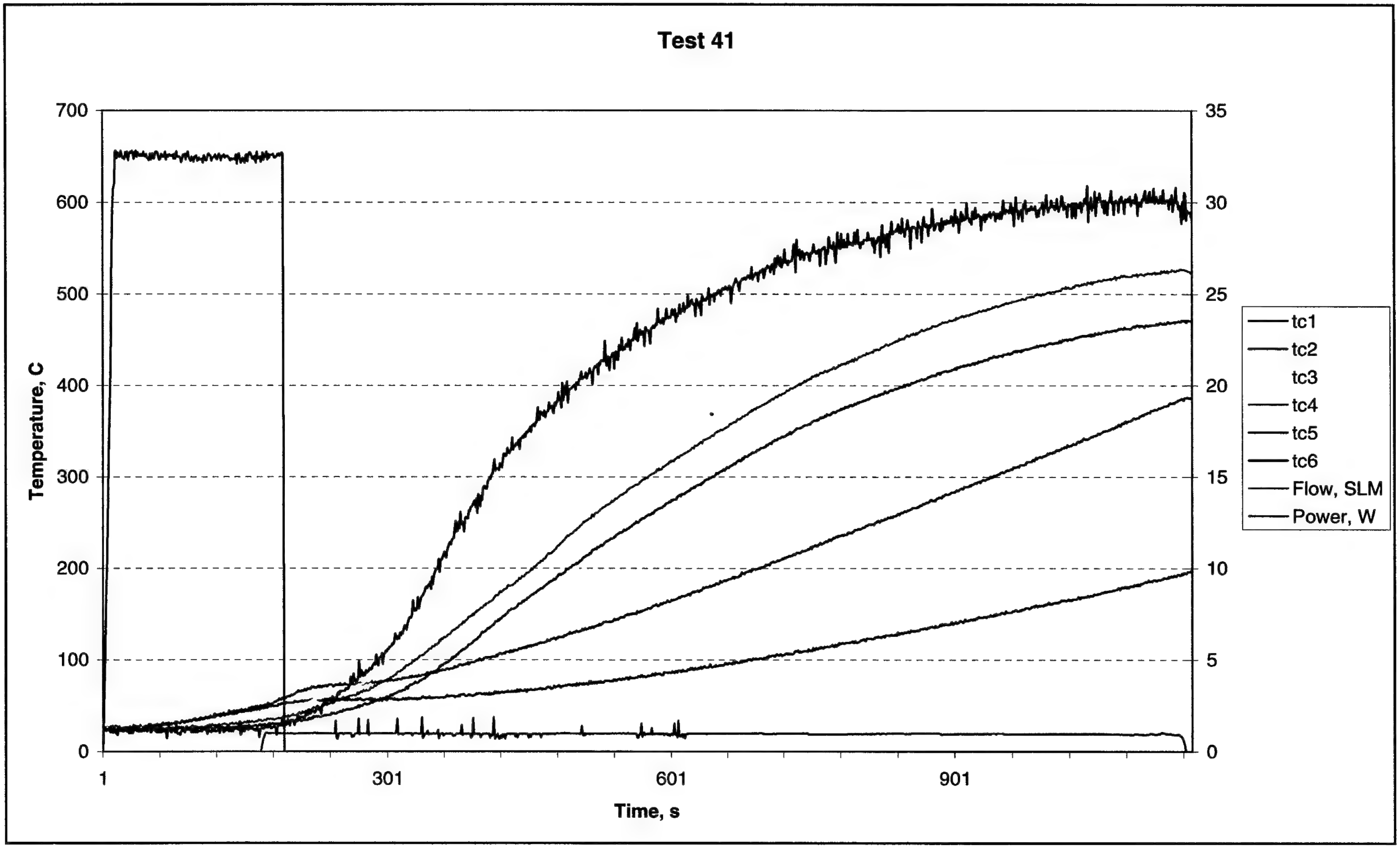
Note:

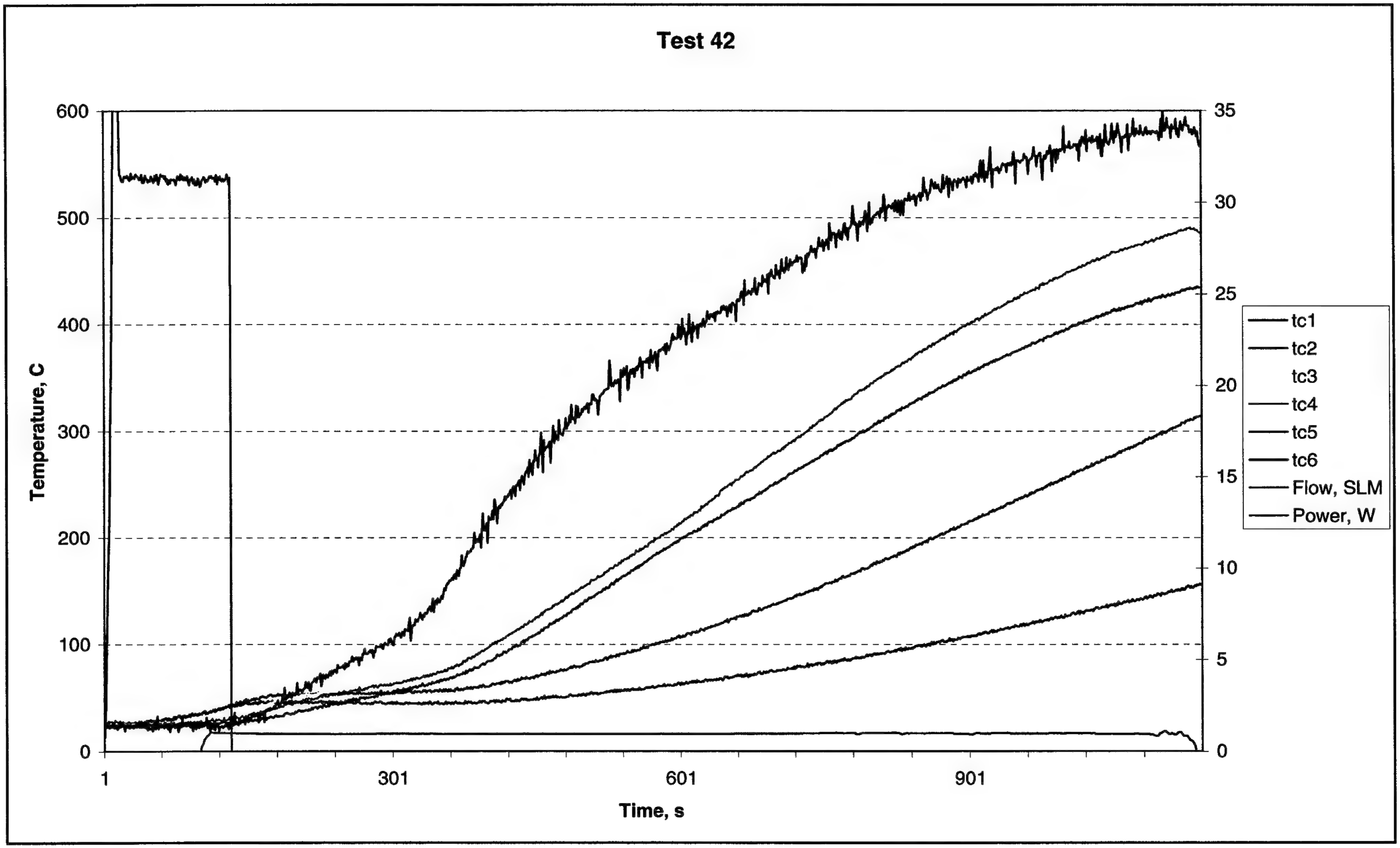
- The following tests were accomplished with 1% (weight) rhodium coated gamma-alumina pellets (ALCOA LD-350 7×14mesh).
- A piece (350mm length) of stainless steel wire (0.6 diameter) was used as a heater.
- Power = electric power
- SLM – standard liter per minute
- W – watt
- J - Joule
- tc - thermocouple


Test 10. Flow-Controlled Self-Sustaining Decomposition of Nitrous Oxide.
Temperature, C
Time, s
1100
1000
900
800
700
600
500
400
300
200
100
0
25
20
15
10
5
0
1
301
601
901
1201
1501
1801
2101
2401
2701
3001
3301
3601
3901
4201
4501
4801
5101
5401
5701
6001
6301
6601
6901
7201
7501
tc1
tc2
tc3
tc4
tc5
tc6
Flow, SLM
Power, W

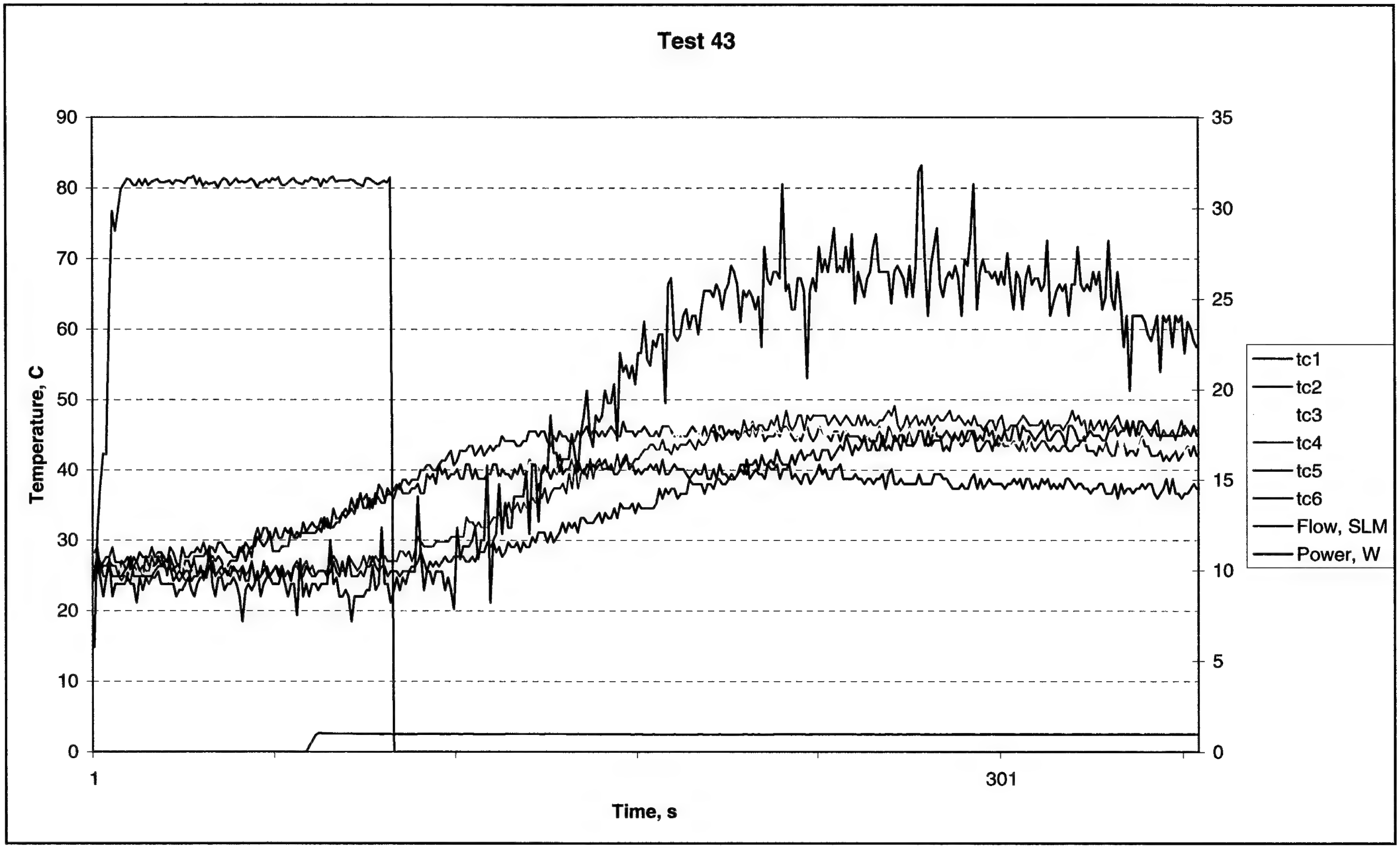

Test 33
Temperature, C
900
800
700
600
500
400
300
200
100
0
35
30
25
20
15
10
5
0
1
301
601
Time, s
tc1
tc2
tc3
tc4
tc5
tc6
Flow, SLM
Power, W


Test 39
Temperature, C
600
500
400
300
200
100
0
35
30
25
20
15
10
5
0
1
301
601
901
Time, s
tc1
tc2
tc3
tc4
tc5
tc6
Flow, SLM
Power, W

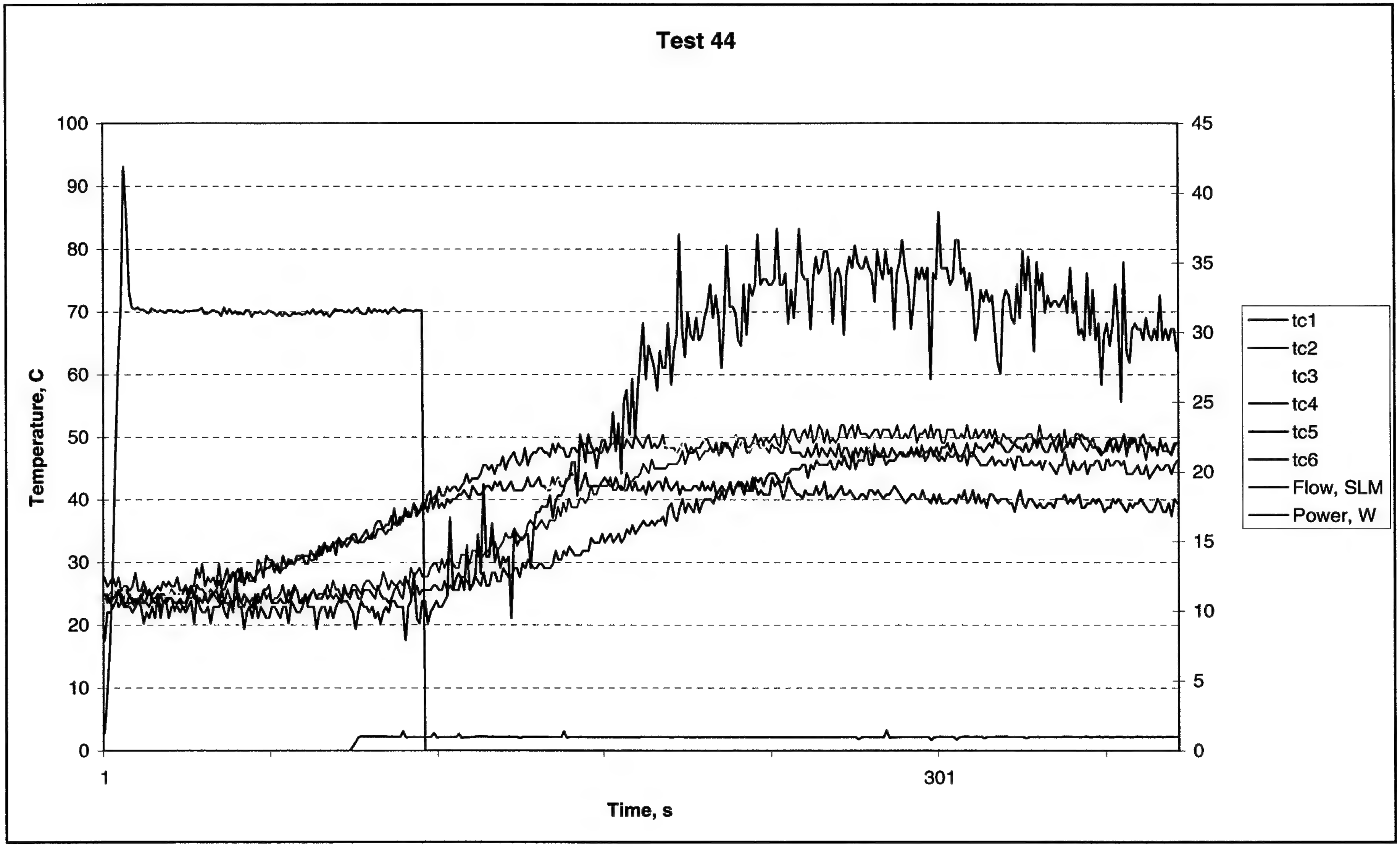

Test 41
Temperature, C
700
600
500
400
300
200
100
0
35
30
25
20
15
10
5
0
1
301
601
901
Time, s
tc1
tc2
tc3
tc4
tc5
tc6
Flow, SLM
Power, W



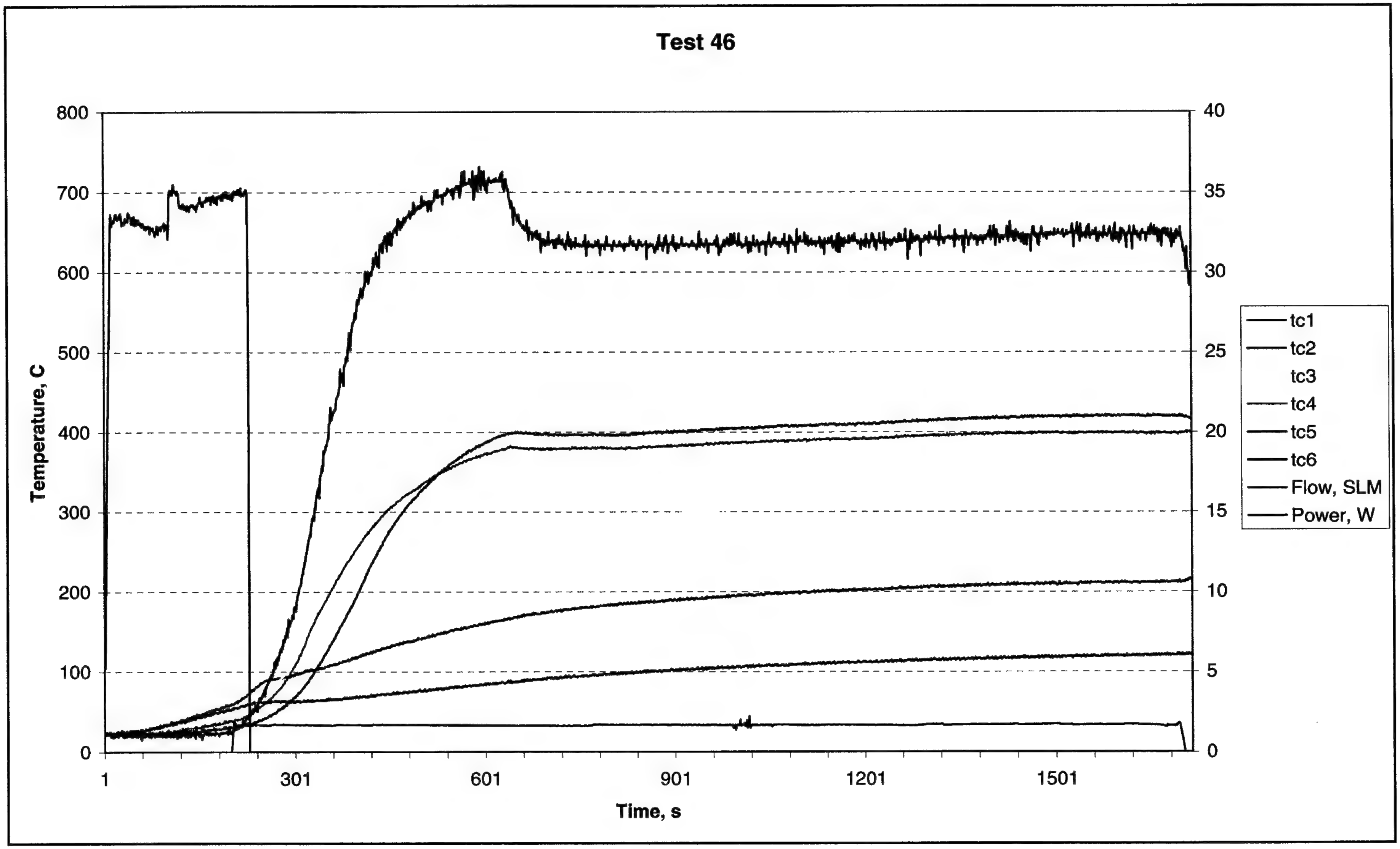
Test 42
Temperature, C
600
500
400
300
200
100
0
35
30
25
20
15
10
5
0
1
301
601
901
Time, s
tc1
tc2
tc3
tc4
tc5
tc6
Flow, SLM
Power, W



Test 43
Temperature, C
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
1
301
Time, s
tc1
tc2
tc3
tc4
tc5
tc6
Flow, SLM
Power, W



Test 44
Temperature, C
Time, s
100
90
80
70
60
50
40
30
20
10
0
45
40
35
30
25
20
15
10
5
0
1
301
tc1
tc2
tc3
tc4
tc5
tc6
Flow, SLM
Power, W



Test 46
800
700
600
500
400
300
200
100
0
Temperature, C
40
35
30
25
20
15
10
5
0
1
301
601
901
1201
1501
Time, s
tc1
tc2
tc3
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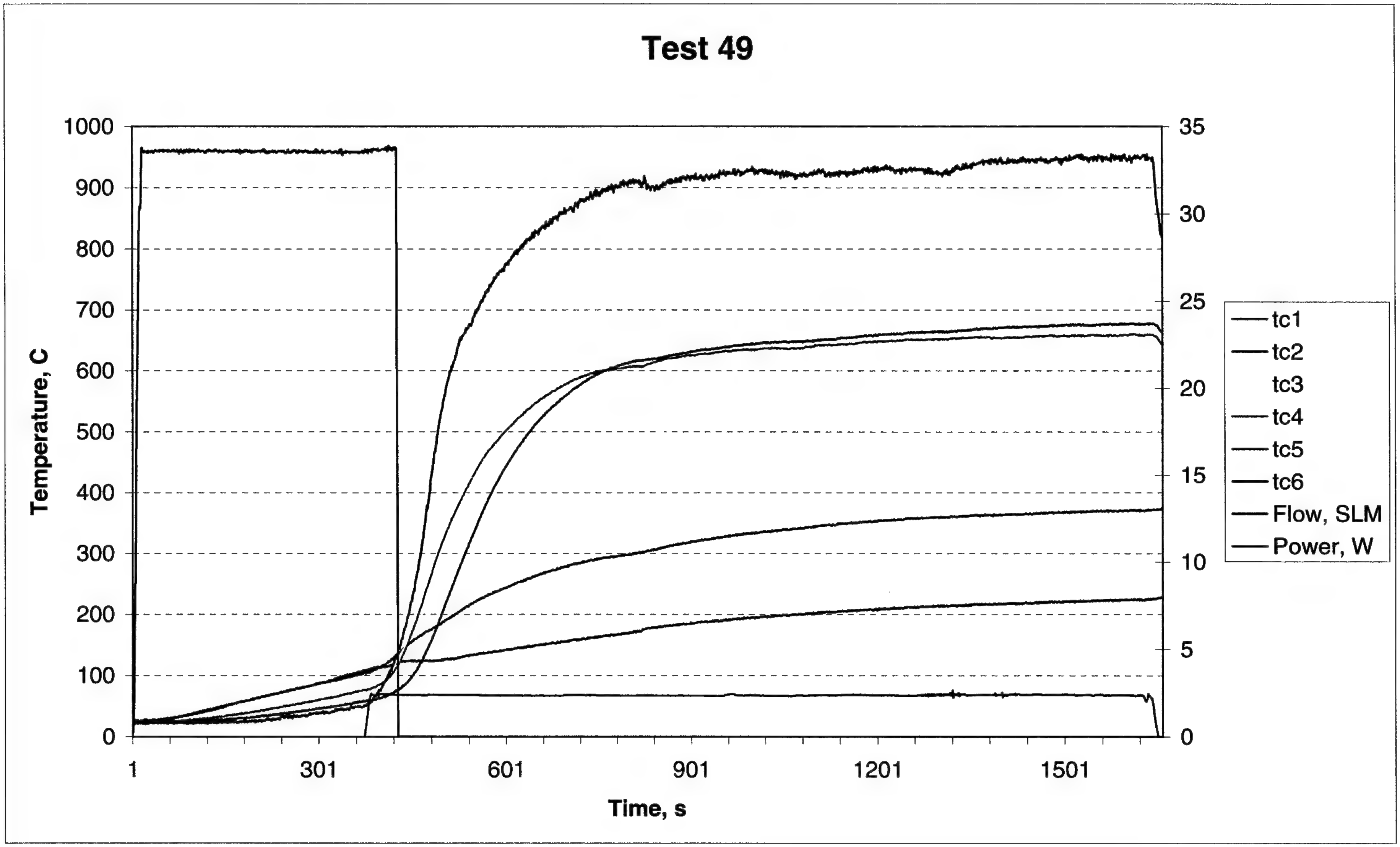
tc6
Flow, SLM
Power, W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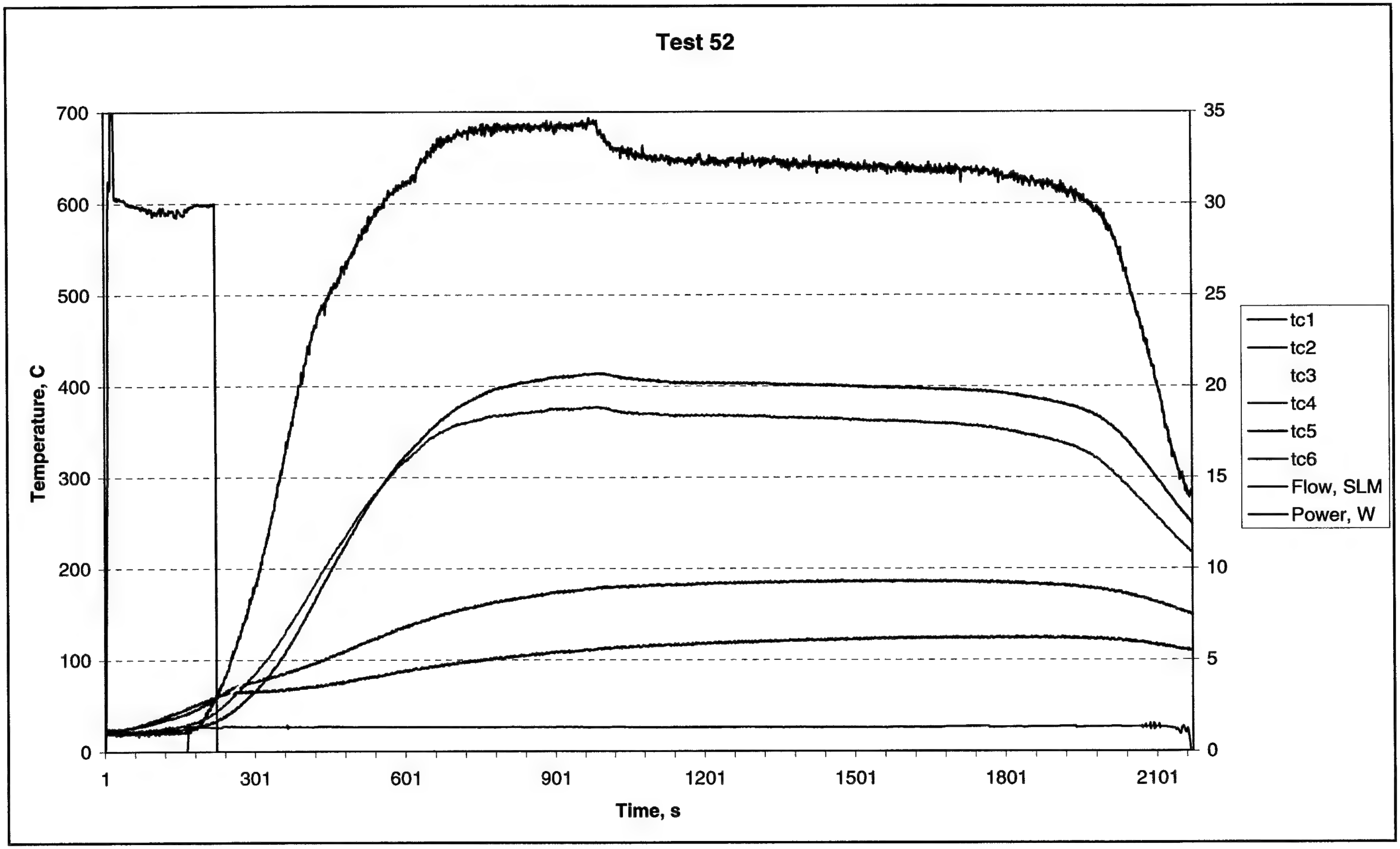
Power, W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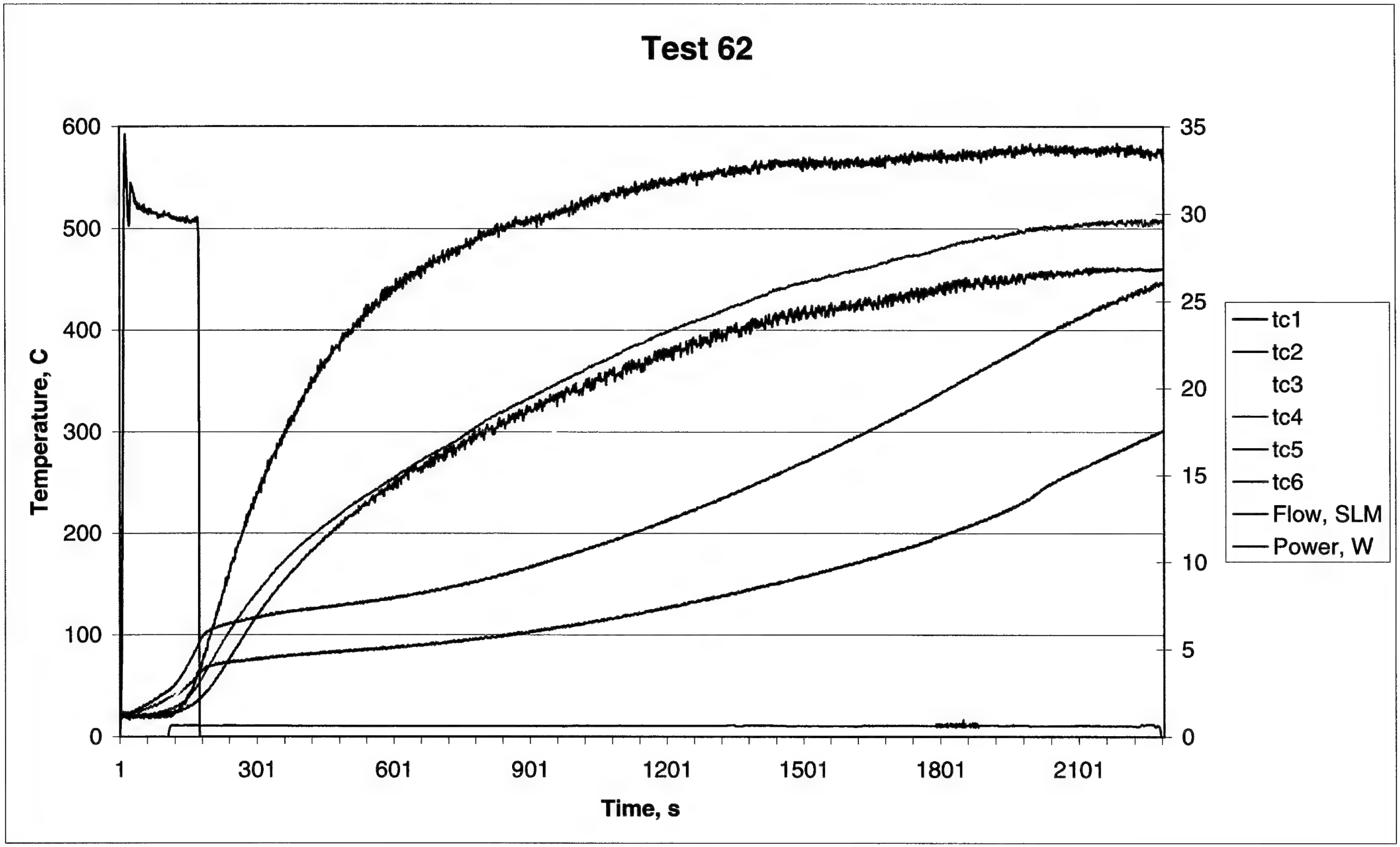
Power, W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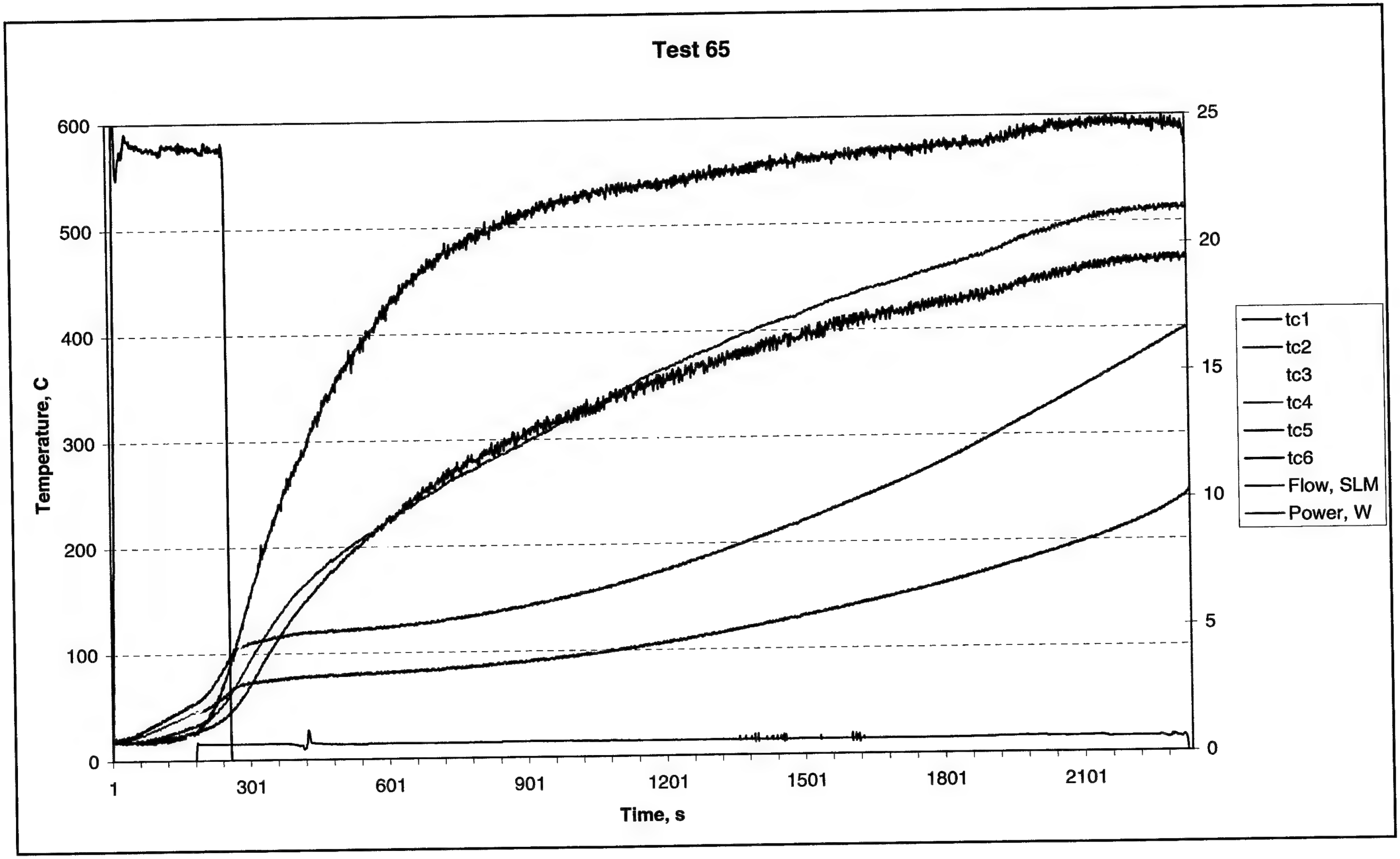
Flow, SLM
Power, W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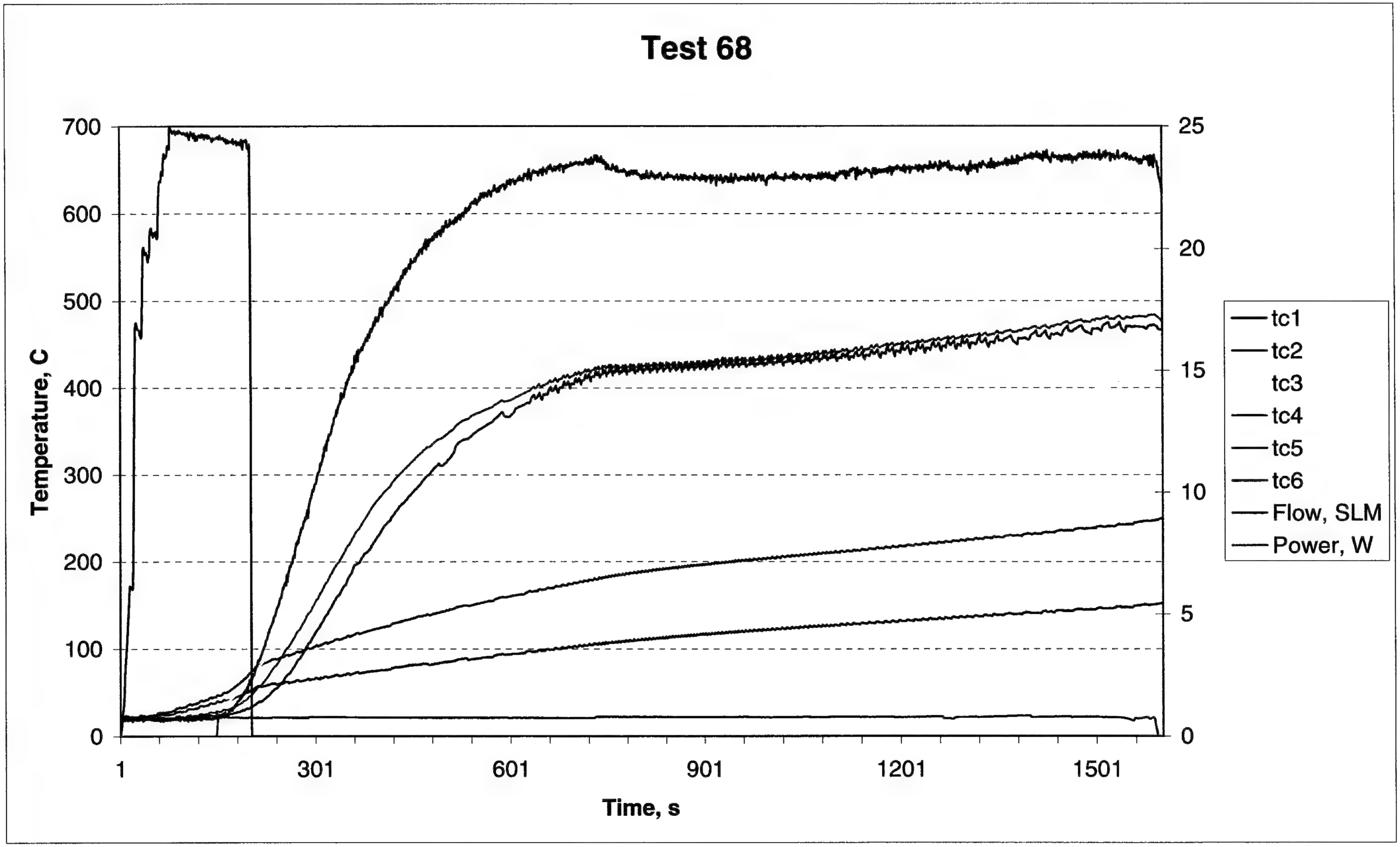
Flow, SLM
Power, W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Time, s
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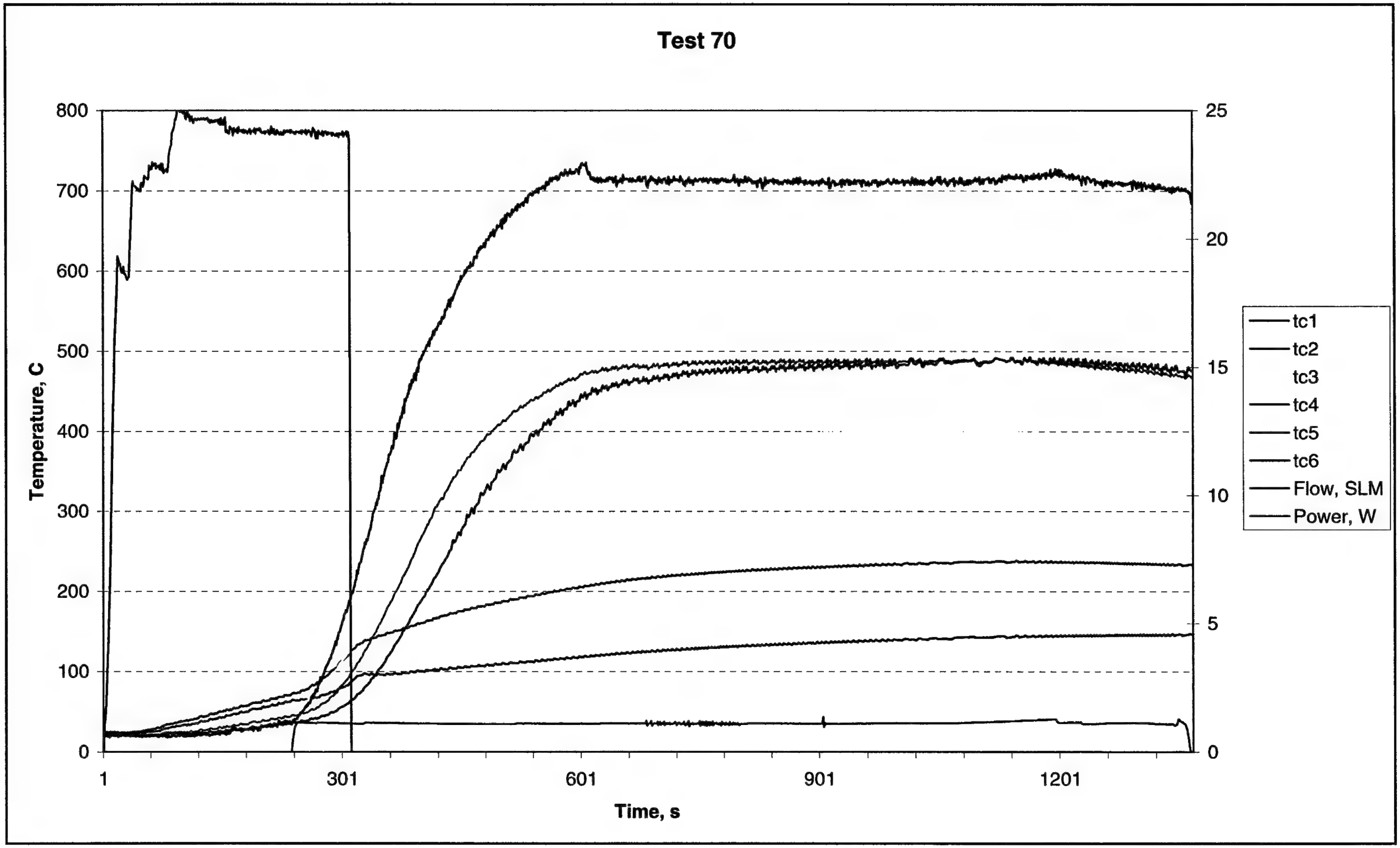
Flow, SLM
Power, W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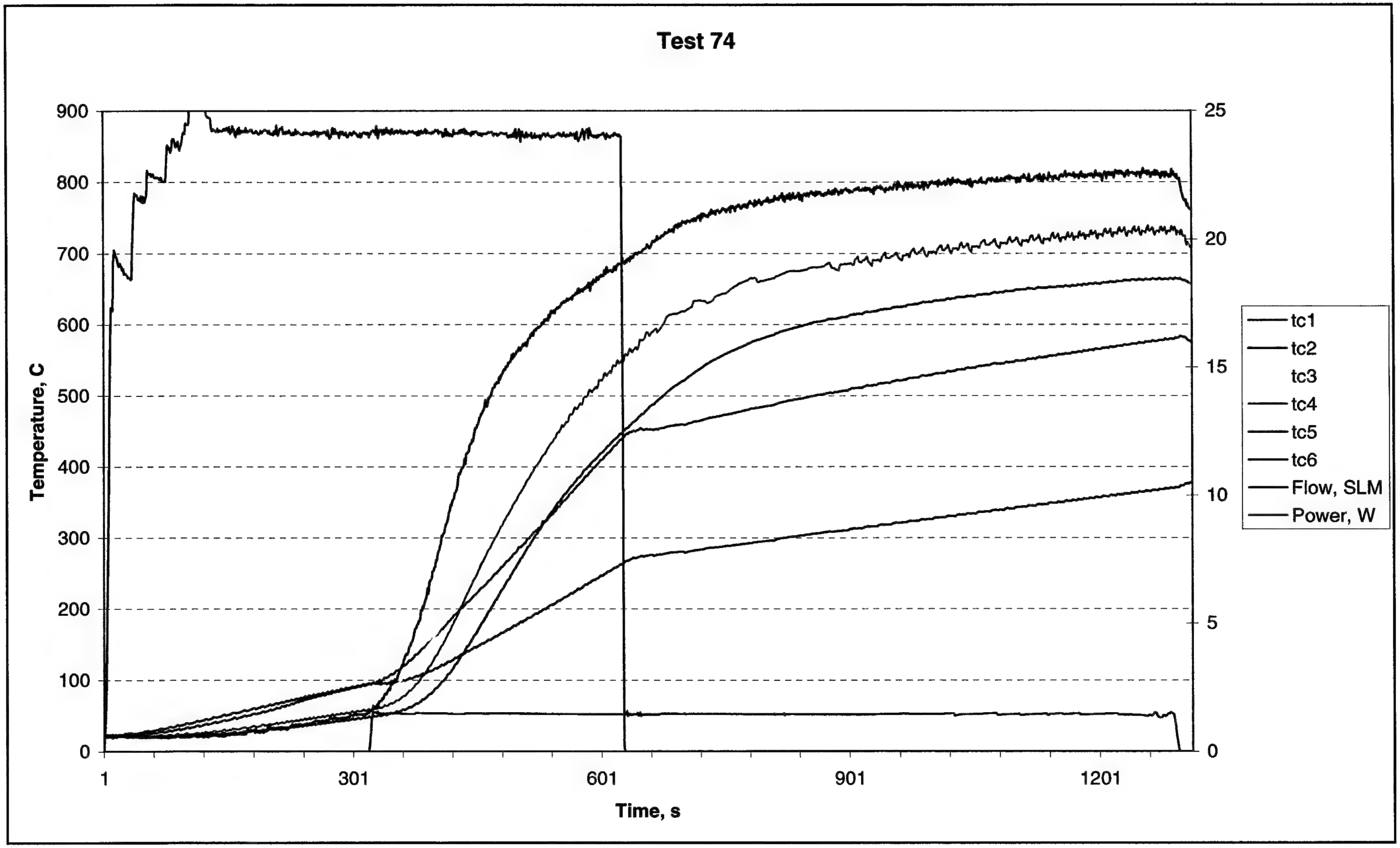
tc6
Flow, SLM
Power, W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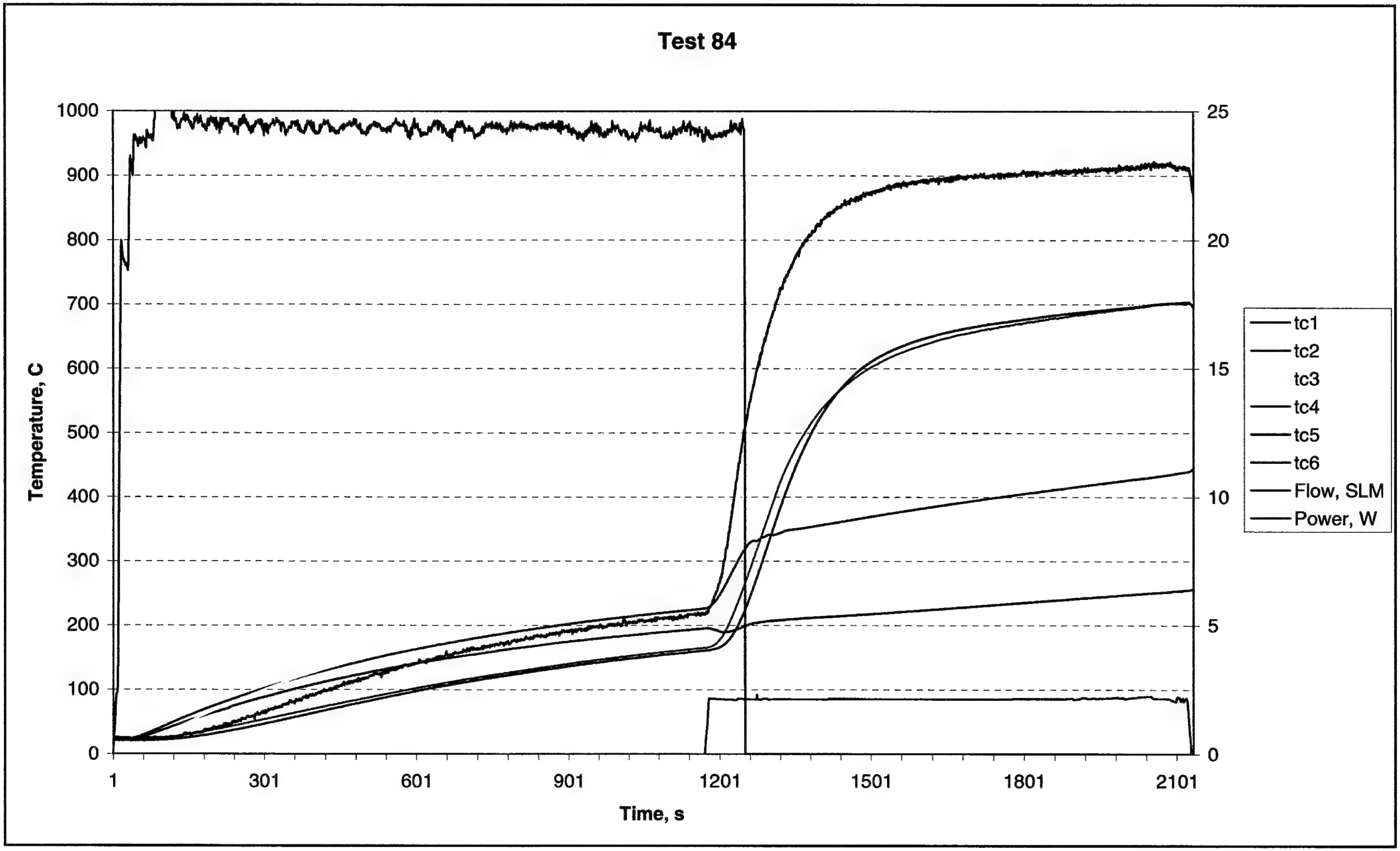
Flow, SLM
Power, W



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301
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1201
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Time, s
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Flow, SLM
Power, W

APPENDIX C

TABLE: N_2O Catalysts

#	Self-supporting	Combined	Catalyst	Support	Form	Power cut-off temperature, °C	Maximum Temperature Achieved, °C	Remarks
1	Y	N	CoO	N/A	Small pieces 1-5 mm	260	854	Hot restarts achievable Sintering
2	Y	N	MnO	N/A	Small pieces 1-5 mm	N/A	368	Not active
3	Y	N	MgO	N/A	Desiccant beads	360	690	Tendency to sintering
4	Y	N	MgO	N/A	Fused pieces	N/A	427	Not active
5	Y	N	γ-Al_2O_3	N/A	Spheres 2-3 mm	N/A	226	Not active
6	Y	N	FeO	N/A	Small pieces 1-5 mm	N/A	150	Not active
7	Y	N	TiO_2	N/A	Small pieces 1-5 mm	N/A	412	When hot turns yellow, retaines colour when cooled
8	Y	N	CeO_2	N/A	Small pieces 1-5 mm	N/A	540	When hot turns yellow, retaines colour when cooled
9	Y	N	SiC	N/A		N/A	N/A	Not active
10	Y	N	NiO	N/A	Small pieces 1-5 mm	N/A	130	Not active
11	N	N	CoO	SiC			791	sintering
12	N	N	FeO	SiC			900	
13	N	N	NiO	SiC			>1130	sintering
14	N	N	Fe_2O_3	γ-Al_2O_3	Spheres 2-3 mm	N/A	170	Not active
15	N	N	FeO	SiO_2	fused lumps	N/A	402	Not active
16	N	N	FeO	MgO	fused lumps	N/A	150	Not active
17	N	N	NiO	MgO	fused lumps	N/A	162	Not active
18	N	N	CoO	MgO	fused lumps	N/A	~350	Not active
19	N	N	NiO	MgO	desiccant beads	150	800	Disactivated at temperatures above 800°C; Irreversible change of colour from green-grey to light green, suspected spinel grow sintering
20	N	N	CoO	MgO	Desiccant beads	200	881	Disactivated at temperatures above 850°C; Irreversible change of colour from black to pink, suspected spinel grow sintering
21	N	N	CoO	ZrO_2	Small pieces 1-5 mm	N/A	150	Not active
22	N	N	NiO	ZrO_2	Small pieces1-5 mm	N/A	~300	Not active
23	N	Y	CoO NiO	MgO	NiO on top	N/A	~200	Not active
24	N Y	Y	CoO FeO	MgO	FeO on top	N/A	120	Not active
25	N Y	Y	CoO Fe_2O_3	MgO	Fe_2O_3on top	N/A	250	Not active
26	N Y	Y	CoO SiC	MgO	SiC on top	380	N/A	Main catalyst exhausted before reaching required decomposition temperature
27	N Y	Y	NiO γ-Al_2O_3	MgO	γ-Al_2O_3 on top	N/A	>1130	Main catalyst disactiveted during the run
28	Y	N	Fuel cell material	N/A	Small pieces 1-5 mm	N/A	145	Not active
29	N Y	Y	CoO NiO	ZrO_2	on top	N/A	N/A	Not active
30	N N	Y	CoO NiO	MgO ZrO_2	on top	N/A	N/A	Not active
31	N Y	Y	NiO NiO	ZrO_2	on top	N/A	820	
32	Y Y	Y	CoO SiC		mixed	N/A	130	Not active

#	Self-supporting	Combined	Catalyst	Support	Form	Power cut-off temperature, °C	Maximum Temperature Achieved, °C	Remarks
33	N Y	Y	CoO SiC	MgO	mixed	160	700	
34	N N	Y	Rh_2O_3 CoO	γ-Al_2O_3 SiO_2	on top	N/A	~800	
35	N N	Y	Rh_2O_3 CoO	γ-Al_2O_3 γ-Al_2O_3	on top	N/A	959	Irreversible change of colour from black to blue Suspected spinel formation
36	N N	Y	Rh_2O_3 CoO	γ-Al_2O_3 γ-Al_2O_3	on top 1500°C pretreated	N/A	805	Suspected spinel formation
37	N N	Y	Rh_2O_3 FeO	γ-Al_2O_3 γ-Al_2O_3	on top	N/A	1120	Irreversible loss of ginger colour for white Suspected spinel formation
38	N N	Y	Rh_2O_3 FeO	γ-Al_2O_3 γ-Al_2O_3	on top 1500°C pretreated	N/A	908	Suspected spinel formation
39	N N	Y	Rh_2O_3 NiO	γ-Al_2O_3 γ-Al_2O_3	on top	N/A	~1000	Irreversible change of colour from light green to light blue Suspected spinel formation
40	N Y	Y	Rh_2O_3 SiC	γ-Al_2O_3	on top	256	1032	Performance degradation
41	N Y	Y	Rh_2O_3 rust	γ-Al_2O_3	on top	250	>1130	Molten steel
42	Y	N	ZrO_2+1%Hf		Small pieces 1-5 mm	500	1142	Irreversible change of colour from grey to white Suspected loss of Hf
43	N Y	Y	NiO NiO	ZrO_2	mixed	500	1538	Active through several restarts
44			LCH-212 Shell-405			450	1163	Catalyst redeposits itself on thermocouple in flow Catalyst material sublimation
45	N	N	Rh_2O_3	γ-Al_2O_3	Spheres 2-3 mm	250	1376	Loss of catalyst from pellet surface catalyst disactivation
46	N	N	NiO	MgO+ ZrO_2		220	786	Irreversible change of colour from green-grey to light green, suspected spinel grow sintering
47	N	N	Fe_2O_3	ZSM-5	Corning monolyth	450	>1100	Zeolite sintering
48	N	N	Rh_2O_3	γ-Al_2O_3	Corning monolyth	300	>1130	Erosion of the monolyth

APPENDIX D

Papers and Reports on Nitrous Oxide Decomposition

- Vadim Zakirov, Jeff Ward, "Catalytic decomposition of nitrous oxide for spacecraft propulsion applications. (Phase 1)", Proposal to EOARD, August 1999.
- Vadim Zakirov, Guy Richardson, "Catalytic Decomposition of Nitrous Oxide for Spacecraft Propulsion Applications (Phase 1: Step 1 – Study"), EOARD Report, September 1999.
- Zakirov, V.A., Lawrence T.J., Sellers J.J., and Sweeting M.N., "Nitrous Oxide as a Rocket Propellant for Small Satellites", 5th International Symposium on Small Satellite Systems and Services, France, 19-23 June, 2000.
- Zakirov, V.A., Goeman V., Lawrence T.J., and Sweeting M.N., "Surrey Research on Nitrous Oxide Catalytic Decomposition for Space Applications", the 14th Annual AIAA/USU Conference on Small Satellites, 21-24 August, 2000.
- Zakirov, V.A., T.J. Lawrence, J.J. Sellers, and M.N. Sweeting, "Nitrous Oxide as a Rocket Propellant", Proceedings of the 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2000.

PROPOSAL SUBMITTED TO
EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT
(EOARD)

Title of Proposal: ***Catalytic decomposition of nitrous oxide for spacecraft propulsion applications. (Phase 1)***

Requested Starting Date: ***September 1st, 99***

Proposed Duration: ***12 months***

Abstract

Advanced small satellites require propulsion for orbit maneuvering, station-keeping, and attitude control. The high cost associated with conventional chemical liquid propulsion systems is a major obstacle for their small satellite applications. A novel nitrous oxide propulsion concept promises an alternative low-cost propulsion system for a small satellite. This concept relies on innovative technique for catalytic decomposition of nitrous oxide gas. The intention of this research programme is to develop and evaluate nitrous oxide mono-propellant thruster applying this technique. Preliminary experimental work has demonstrated that this is achievable. The initial research programme is considered to have four primary objectives. To achieve these objectives the proposed research programme has been divided in 3 work packages.

Statement of Work

A. INTRODUCTION

Advanced small satellites require propulsion for orbit manoeuvring, station-keeping, and attitude control. The power system of, for example, micro-satellite class (< 75kg) spacecraft is capable of delivering 14W (average) per orbit and can not handle the high power consumption demands (typically > 100W) associated with electric propulsion systems. Low specific impulse performance of cold-gas propulsion (typically 65s) aggravated by severe volume constraints (propulsion envelope volume of about 7 litres), limit the range of small satellite's orbital transfer manoeuvres to approximately 25m/s. Solid rocket motors are limited by their inability to be fired more than once. The high cost associated with conventional chemical liquid propulsion systems is a major obstacle for their small satellite applications.

A novel nitrous oxide propulsion concept promises an alternative low-cost propulsion for small satellites. This concept relies on innovative technique for catalytic decomposition of nitrous oxide gas. A catalyst lowers the activation energy and thus the decomposition takes place at much lower temperatures.

This principle can be used to generate a hot nitrogen-oxygen mixture that may combust a fuel in a bi-propellant motor or can simply be exhausted through a nozzle as a mono-propellant. Theoretical vacuum specific impulse of nitrous oxide mono-propellant thruster is ~205s. This is substantially higher than the demonstrated specific impulse performance of the nitrous oxide resistojet thruster achieved during the *Mark-III* vacuum testing which was 140s. [Resistojet Research at the University of Surrey, Internet: http://www.ee.surrey.ac.uk/CSER/UOSAT/research/resisto.htm]. The proposed nitrous oxide decomposition method will provide increased performance compared to the *Mark-III* resistojet thruster. The thrust time delay will also decrease from 15min to the order of a few seconds. Additionally the power level required to operate the system will decrease from 100W continuous to about 50W for a 10s of seconds (start-up). The thruster mass and size will also be reduced. Preliminary experimental work has demonstrated that all of these goals are achievable.

There is also the potential for further performance by injecting fuel downstream of the catalyst forming a hybrid or liquid bi-propellant rocket motor.

The multiple-mode nitrous oxide fed propulsion system for small satellites including, for example, cold-gas, mono-propellant and/or bi-propellant thrusters would provide the spacecraft with all necessary functions to fulfill its mission. The proposed technique for nitrous oxide catalytic decomposition will make this possible.

The further benefit of this technique is that its space application may be extended to hot gas generation on-board of a spacecraft. This hot oxygen-rich gas mixture may be used for pressurisation of propellant tanks, heat and power (turbine drive) generation, and even for life support system (breathing nitrogen-oxygen mixture) on-board of the spacecraft.
Nitrous oxide is stored as a self-pressurizing liquid of 745kg/m^3 density at 21°C temperature under 52.4 This self-pressurizing feature provided the potential for a simple, inexpensive storage system.

B. TECHNICAL PROPOSAL/DESCRIPTION OF WORK
It is the intention of this research programme to develop and evaluate a nitrous oxide mono-propellant thruster. In this unit a flow of nitrous oxide is injected into the decomposition chamber. Upon injection, nitrous oxide starts to decompose on an electrically heated rhodium (Rh) wire, which is, in fact, an igniter made of catalyst material. It has been assessed that a rhodium wire of 0.127mm diameter can be heated in 1s to 750°C by a 10A current. This temperature shall activate the rhodium wire to begin catalytic decomposition of the nitrous oxide (the total electrical power required for heating of the wire is ~50W). The heat generated by initial nitrous oxide decomposition will rise the temperature of the main catalyst. This temperature rise will activate the catalyst to decompose the rest of nitrous oxide. The start-up transient is in the order of a few seconds. After ignition the electrical power to rhodium wire may be cut-off. The self-sustaining catalytic decomposition of nitrous oxide will generate enough heat to rise the temperature of exhaust products to somewhat above 1100°C.
This oxygen-rich gas mixture may be directed through the converging-diverging nozzle to create thrust or combined with a fuel for a further increase in performance.

This initial research programme is considered to have four primary objectives

i) Self-sustaining decomposition of nitrous oxide inside the thruster should be achieved for different catalysts
ii) Nitrous oxide gas "light-up" by rhodium wire should be demonstrated.
iii) To demonstrate the potential of nitrous oxide compared with hydrogen peroxide, and hydrazine.
iv) To characterize the performance of a thruster under various operating conditions to gain an understanding sufficient to design a flight quality motor.

To achieve these objective the research programme has been divided in 3 work packages:

<u>Work package 1 – Study (2 months)</u>
A paper study will be undertaken to compare nitrous oxide mono-propellant thrusters with hydrogen peroxide and hydrazine mono-propellant thrusters. A test plan for the nitrous oxide mono-propellant thrusters experimental work will also be produced. The results of the background work will be given as a report which will include:

1. A system trade study (specific impulse, propellant volume and mass) for 3 different (nitrous oxide, hydrogen peroxide, and hydrazine) mono-propellant thrusters for micro-satellite bus.
2. The test plan.
3. The testing design. The magnitude of thrust will be defined along with the thruster size, mass flow rates etc.

<u>Work package 2 – Testing (6 months)</u>
Four types of catalysts will be investigated: iron oxide and rhodium coated on different matrix and pellet substrates. A test programme will aim to explore the operational envelope and catalyst lifetime. All test will be conducted at sea level. The following parameters will be measured and/or varied.

1. Nitrous oxide mass flow rate (variable parameter)
2. Nitrous oxide initial temperature (measured parameter)
3. Decomposition (chamber) temperature (measured parameter)
4. Exhaust product temperature (measured parameter)

5. Decomposition chamber outside wall temperature (measured parameter)
6. Insulation outside wall temperature (measured parameter)
7. Rhodium wire temperature (passive measurement) (measured parameter)
8. Electric power, current for rhodium wire heating (variable parameter)
9. Chamber pressure (measured parameter)
10. Feed pressure (measured parameter)
11. Start-up transient time (measured parameter)

Additional testing work will also be undertaken to evaluate the effectiveness of design changes resulting from suggestions of work package 3.

Work package 3 – Analysis (4 months)

From the experimental data an operational envelope for each catalyst will be defined. Once the main parameters are known, an analytical simulation will be performed to minimise heat losses from the system. Nitrous oxide injection into the chamber will be optimised. Improvements to the thruster's design will be suggested to enhance performance.

Deliverables

As discussed above a report will be provided summarizing the results of preliminary paper study. A final report will also be produced. The final report will describe the apparatus, test set-up and measurement techniques used for testing, contain the recorded values of pressures, temperatures, nitrous oxide mass flow rates, and discuss the results obtained. A proposal for further development and design of the nitrous oxide thruster will be presented.

C. FACILITIES/EQUIPMENT

The existing SSC's equipment and facilities will be used. Extensive use will be made of the Surrey Space Centre (SSC) laboratories, rocket firing facilities, data acquisition systems, and experimental apparatus.

D. QUALIFICATIONS OF PERSONNEL

Vadim Zakirov, Engineer, Space Power and Propulsion, Moscow Aviation Institute (Russia), Engineer, Russian Research Centre "Kurchatov Institute", Division of High Power Reactors (Russia), MS, Aerospace Dept., University of Florida, (U.S.A.), Currently is MPhil student, University of Surrey, (U.K.) working on HTP concentrating equipment and HTP decomposition catalysts for propulsion systems related to helicopters and space vehicles.

Guy Richardson, B.Eng (hons) PhD (Surrey), Surrey Space Centre, Lecturer (Structures / Propulsion). 11 year research experience including mechanical testing, structural, thermal and dynamic numerical analysis (application and algorithm development), design optimisation strategies, hybrid rocket propulsion.

Malcolm Paul, Surrey Space Centre engineer, HNC Mechanical Engineering, 35 years of rocket testing experience.

Volker Goeman, MSc Chemistry, University of Hanover, Germany, Dr. Phil. nat., University of Frankfurt/Main, Germany. Three years of research experience of N_2O-decomposition at Daimler-Benz Aerospace Dornier, Friedrichshafen, Germany.

E. SCHEDULE OF REPORTS

Step 1—Study report will be submitted by the end of October 1999.

Final report for Phase 1 should be submitted to EOARD by end of August, 2000.

Cost Proposal
For Research Period Sept 1st 99 to Aug 31st, 00

1. Consumables:	
a. N_2O supply	$400
b. Catalyst manufacture	$3700
c. Rhodium wire	$2500
d. Thermocouples	$500
e. Miscellaneous (pipe fittings, valves, connectors, insulation etc.)	$2000
f. Thruster reaction chambers, end caps and nozzles	$3000
2. Labor:	
a. Academic (60 man days)	$15,000
b. Technical support Total Man-hours (60 man days)	$15,000
3. Overheads:	$7900
Total	**$50000**

REPORT

CATALYTIC DECOMPOSITION OF NITROUS OXIDE FOR SPACECRAFT PROPULSION APPLICATIONS (Phase 1: Step 1 -- Study)

by
Vadim Zakirov
Guy Richardson

SUBMITTED TO
EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT (EOARD)
TO COMPLETE PHASE 1 DELIVERABLE

SEPTEMBER 1999

1. MONO-PROPELLANT/RESISTOJET THRUSTER PERFORMANCE COMPARISON

Three mono-propellant propulsion technologies have been selected for this comparison. Nitrous oxide mono-propellant thruster theoretical performance is compared to that of hydrogen peroxide and conventional hydrazine thrusters for micro-satellite applications. (see Table 1)

The comparison reveals that nitrous oxide mono-propellant thruster is capable of moderate theoretical specific impulse performance 16% lower than that of for hydrazine but 15% higher than that of for hydrogen peroxide thrusters. A practical value of specific impulse for nitrous oxide mono-propellant thruster is to be determined for comparison with those of hydrogen peroxide [Frolov98, Whitehead98] and hydrazine [KM] thrusters. The results of the comparison of total satellite velocity change per propellant and pressurant mass are illustrated in Figure 1. Storage density of liquefied nitrous oxide is 26% lower than that of hydrazine and 45% lower than that of hydrogen peroxide. However, because of low vapour pressures, hydrazine and hydrogen peroxide require pressurant that usually increases storage system volume by one third. Figure 2 illustrates this result for the case of micro-satellite.

Propellant handling is a significant issue. Nitrous oxide handling requires no safety equipment, while splash protection is necessary for hydrogen peroxide. Complete protection is essential for hydrazine handling. Nitrous oxide presents no fire or explosion hazard, while hydrogen peroxide may spontaneously ignite on contact with an carbohydrates. Contaminated hydrogen peroxide is unstable and presents serious explosive hazards. High fire and explosive hazards are associated with hydrazine.

Storage temperature range of nitrous oxide varies as a function of vapour pressure, tank design pressure and ullage volume. In general, this range is broader than that of hydrogen peroxide and hydrazine. The trades are discussed in details later in this report. Storage temperature range for hydrogen peroxide varies as a function of its concentration. For the case of 89% strength hydrogen peroxide low temperature limit is defined by freezing point of -12°C. Five degree margin between low operational limit and freezing point is a precaution against sloshing. The similar estimate is applied to hydrazine that has freezing point of about 2°C. Although the boiling temperature of hydrogen peroxide is 141°C the strong temperature dependence of its decomposition rate doubling approximately every 8°C starting from freezing point [JANNAF84] limits the storage temperature to below 38°C. In the case of hydrazine, the upper storage temperature is limited to 40°C although the its boiling point is 113°C.

Although nitrous oxide mono-propellant thruster has yet been flown, the feed system currently undergoes testing on-board of the *UoSAT-12* mini-satellite. Hydrogen peroxide mono-propellant thrusters were flown on *SYNCOM II* satellite [McCormick65], *Scout* [Willis60] and *Centaur* [Whitehead98] rockets, etc. [Sellers96] Presently hydrazine mono-propellant thruster is a conventional extensively used space technology [Sutton92].

The calculated main design parameters of nitrous propulsion system for micro-satellite are presented in Table 2.

The lower chamber pressure is desirable for self-pressurising system because more gas will be consumed before the pressure in the tank will drop below the operational limit. The other advantage of lower chamber pressure is that at the low thrust level (1N) the bigger diameter of nozzle throat will be easier to manufacture, and the friction losses will be lower. Finally lower chamber pressure is preferable for chemical reaction with increasing volume of products according to Le Chatelier's principle [Atkins97].

Table 1. Properties of selected mono-propellants.

Propellant	Nitrous Oxide	Hydrogen Peroxide	Hydrazine
Chemical Formula	N_2O	H_2O_2	N_2H_4
Specific Impulse (theoretical), s	206	179	245
Specific Impulse (quoted), s	unknown	100-150	226-235
Storage Density, kg/m^3	745 @ 21°C 52.4 bar	1347	1004
Vapour pressure	50.8bar @ 20°C	0.00345bar @ 20°C	0.0214bar @ 26.7°C
Toxicity	Non-toxic	Burns skin	Very Toxic
Flammability	Non-flammable	Non-flammable	Flammable
Storage Temperature Range, °C	-34 – 50	-7 – 38	9 – 40
Storability	Storable	Storable (decomposes)	Storable
Flight Heritage	feed system UoSAT-12	flown	flown

Notes: All propellants are stored in liquid state. Hydrogen peroxide is 89% strength. Theoretical specific impulse data obtained for nozzle expansion ratio of 200.

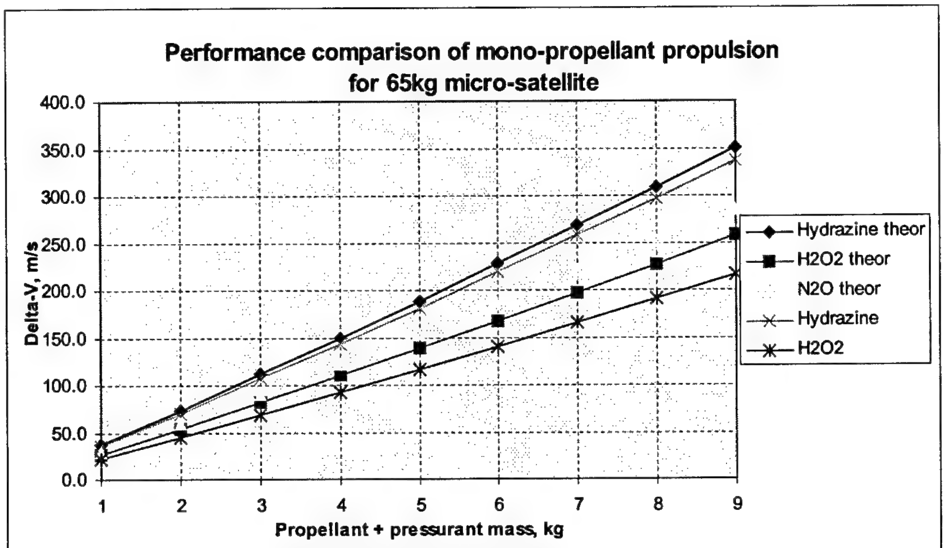


Figure 1. Mono-propellant performance comparison per propellant mass.

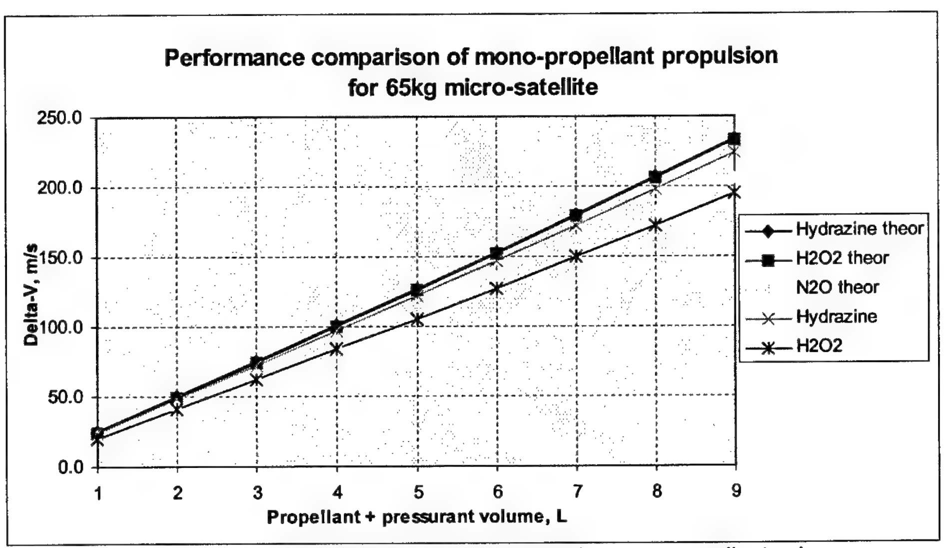


Figure 2. Mono-propellant performance comparison per propellant volume.

Table 2: Calculated performance of nitrous oxide propulsion for micro-satellite.

Parameter	Value		Units
Micro-satellite			
Initial mass	65		kg
Delta-V	100		m/s
Propulsion			
Propellant	N_2O	N_2H_4	
Specific Impulse	190	226	s
Mass of propellant	3.7	3.15	kg
Volume of propellant	5.5	4.2	L
Thruster			
Mass		0.33	kg
Size		$\varnothing$ 32 × 146	mm
Thrust	1		N
Propellant mass flow rate	0.54	0.45	gm/s
Chamber pressure	3	7-28	atm
Nozzle			
Throat diameter	1.5		mm
Expansion ratio	200		

2. THEORETICAL PERFORMANCE

2.1. Decomposition

Nitrous oxide decomposes according to the summary reaction equation:

$$N_2O \rightarrow N_2 + \tfrac{1}{2}\ O_2 + \text{Heat}$$

The amount of heat released (at normal conditions) in this exothermic reaction is 82 kJ/mole.
At normal conditions the activation energy barrier for the reaction initiation is about 250-270 kJ/mole. Therefore, the nitrous oxide must be heated up to 1030°C to find any decomposition.

2.2. Thermodynamic analysis

Thermodynamic analysis has been undertaken to assess the theoretical performance of the thruster.
Theoretical specific impulse performance of nitrous oxide mono-propellant thruster is evaluated using the *USAF ISP* computer code written by Curt Selph.
The result of the computation is shown in Figure 3. The specific impulse performance monotonically rises with increasing chamber (decomposition) temperature until it reaches its maximum at about 1640°C. The computation using tables of thermodynamic properties [Horvarth75, JANNAF71, JANNAF85] gives similar result regarding the maximum decomposition temperature. Figure 4 illustrates the balance between the heat generated by decomposition and the heat required to raise the initial temperature of nitrous oxide to the process temperature. The intersection point on the graph represents the limit at which all generated heat is consumed by heating the propellant to the reaction temperature so that no more heat can be generated internally. The further increase in the process temperature is possible only if external heat is added to the system (for example, initial propellant pre-heating is employed). In both of the approaches the ideal gas assumption is used for calculation of the thermodynamic performance of the decomposition process.[DeHoff93, Humble95, Rogers92]
The heat transfer out of the thruster makes theoretical decomposition temperature, and thus specific impulse performance, unattainable. Therefore, minimisation of heat losses out of the thruster increases its performance.

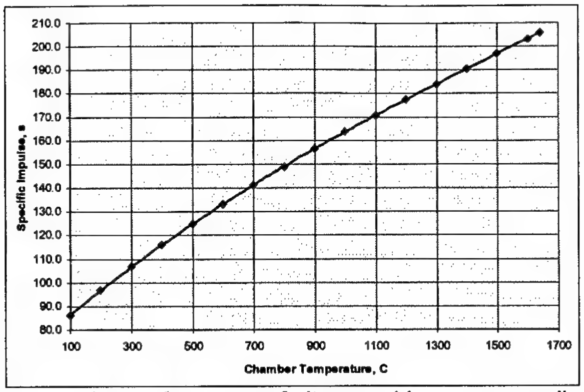


Figure 3. Theoretical specific impulse performance of nitrous oxide mono-propellant thruster as a function of chamber temperature.

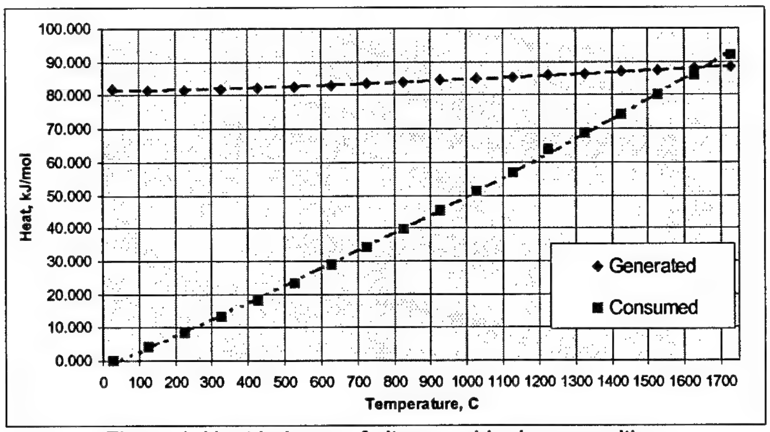


Figure 4. Heat balance of nitrous oxide decomposition.

3. THRUSTER DESIGN

3.1. Nozzle Expansion Ratio

As shown in Figure 5, rapid increase in specific impulse can be observed at rising nozzle expansion ratio up to about 100. Then, the gain slows down sharply so that the significant increase in nozzle expansion ratio corresponds to slight change in specific impulse performance.

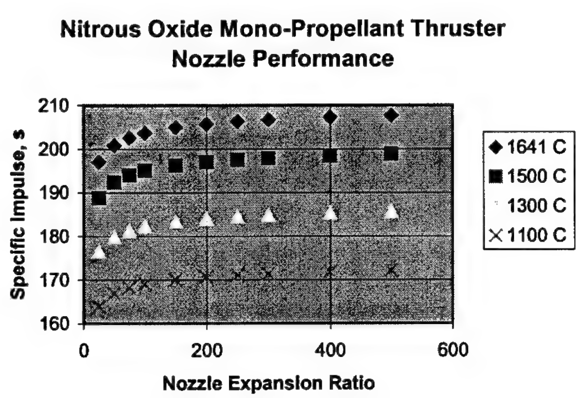


Figure 5. Specific impulse performance of nitrous oxide mono-propellant thruster as a function of nozzle expansion ratio and chamber temperature.

The optimum value of nozzle expansion ratio controls the size of the nozzle. Size of the nozzle is a function of chamber pressure. Therefore, the trade of the nozzle size versus chamber pressure is given in Figures 6 & 7 for the case of conical nozzle with 15° half-angle.

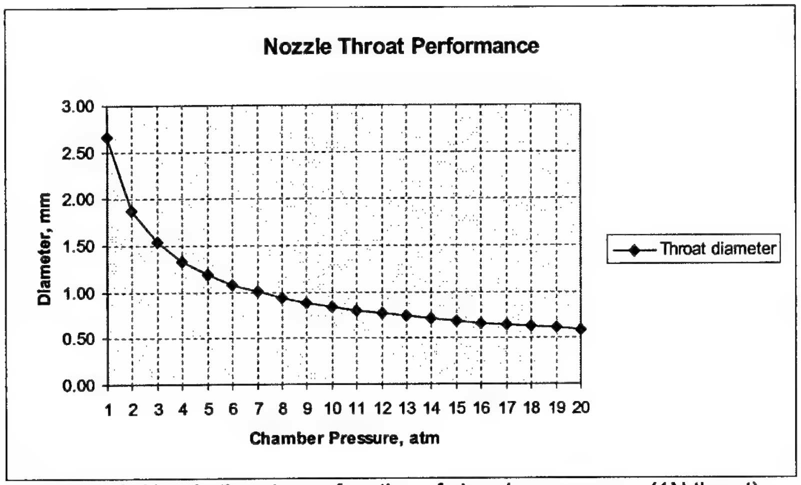


Figure 6. Nozzle throat as a function of chamber pressure. (1N thrust)

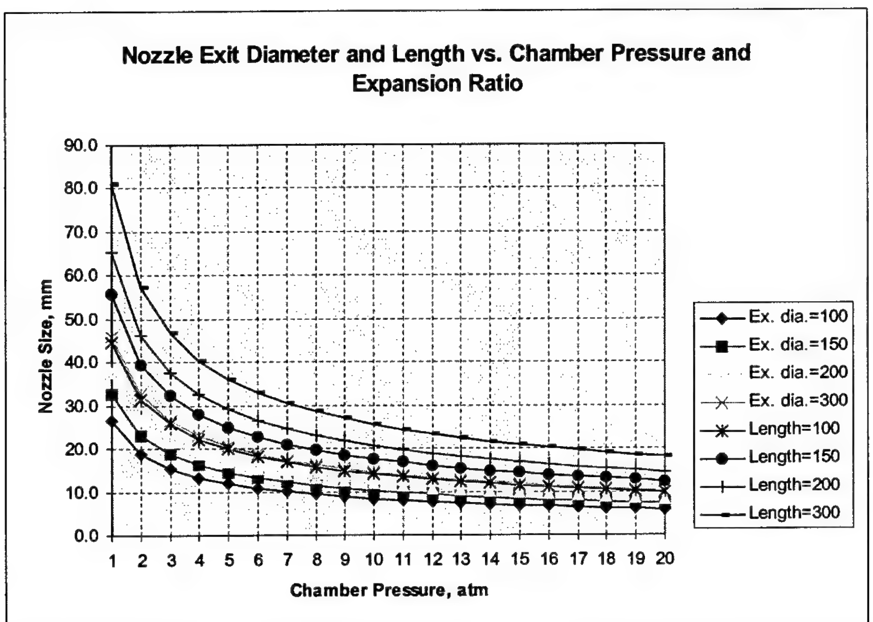


Figure 7. Nozzle size (length and exit diameter) as a function of chamber pressure and expansion ratio. Conical shape nozzle assumed. (15° half-angle, 1N thrust)

4. STORAGE

Nitrous oxide is classified by the Department of Transportation (DOT) as a non-flammable, compressed gas and is shipped with the required "Green Label". [Matheson80]

When dispensed in a pressurised tank, the nitrous oxide exists in two forms, gas and liquid. The pressure of a full tank, regardless of size, will read approximately 52 atm. Since nitrous oxide is a liquefied gas at room temperature, the tank pressure will remain constant as long as any liquid remains in the tank. When the tank has been used to the point where a liquid phase no longer exists (after approximately 75% to 80% consumption), then the pressure will start to drop. If a more

accurate accounting of the tank's volume is necessary, then one can weigh the tank to make the determination.
Above the critical temperature of 36.5°C nitrous oxide will convert completely to a gas and the discharge of the tank content will show a steady drop in pressure. [Matheson80]
Chilling the tank lowers the pressure dramatically and will also lower a sustainable flow rate of the nitrous oxide.
Nitrous oxide does not require pressurisation system. It can be stored as liquid or compressed gas (above the critical point) through the wide temperature range limited perhaps by triple point [Matheson80] on the lower end and thermal decomposition temperature of 520°C [Oxford96] on the upper end of the range. The maximum storage temperature limit is dependant on provisioned tank pressure and ullage volume. The practical maximum operational temperature number for designed tank pressure of 200bar would be 50°C. However, it increases while the propellant is consumed. The recommended low operational temperature is at -34°C. This would allow tank operational pressure (nitrous oxide vapour pressure) stay above 11bar.
Pressure of gaseous nitrous oxide can be calculated by Benedict-Webb-Rubin (BWR) equation of state within temperature range from -30°C to 150°C, for densities up to 905kg/m^3, and maximum pressure of 200atm.[Walas85]:

$$P = RT\rho + \left(B_0RT - A_0 - \frac{C_0}{T^2} \right)\rho^2 + (bRT - a)\rho^3 + a\alpha\rho^6 + \frac{c}{T^2}\rho^3\left(1 + \gamma\rho^2\right)\exp\left(-\gamma\rho^2\right)$$

where P – gas pressure, atm;
R – universal gas constant $R=0.08206$ atm·L/mol/K;
ρ – gas density, mole/L;
T – gas temperature, K;
A_0, B_0, C_0, a, b, c, α, γ – gas constants of equation.
This equation is used to predict nitrous oxide vapour pressure variation inside storage tank as a function of temperature (see Figures 8 & 9).

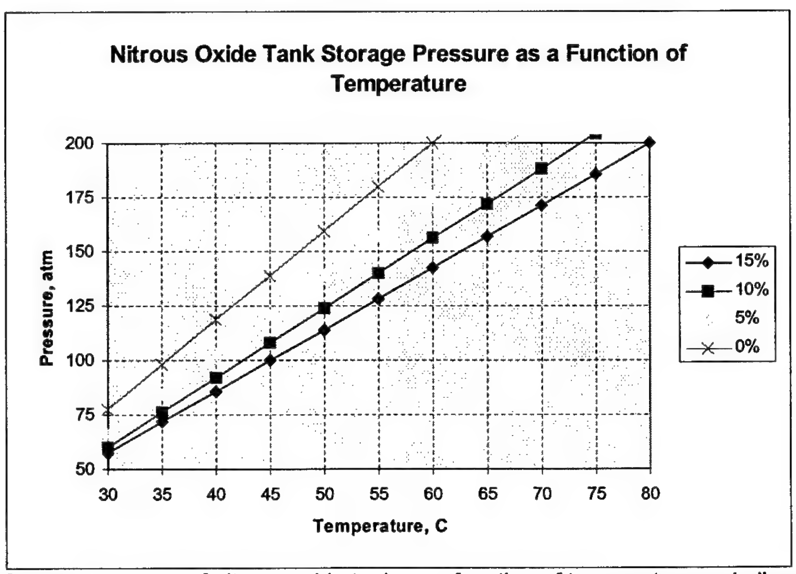


Figure 8. Storage pressure of nitrous oxide tank as a function of temperature and ullage volume.

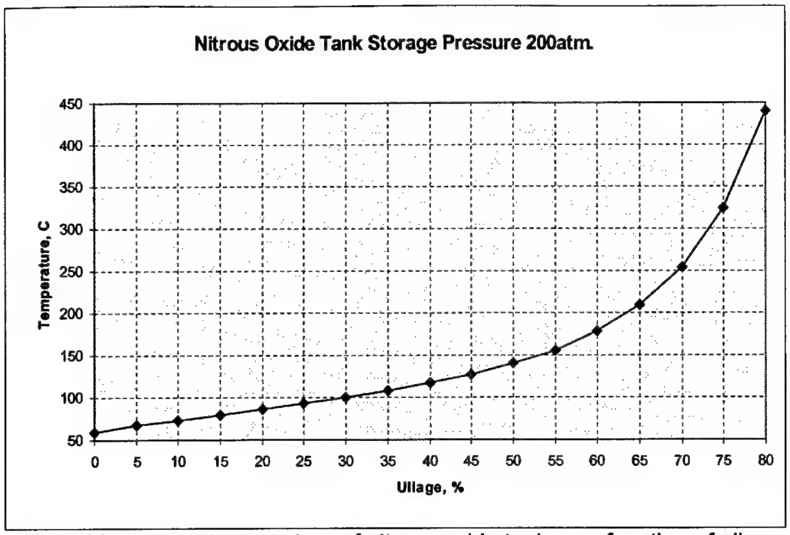


Figure 9. Allowable storage temperature of nitrous oxide tank as a function of ullage volume.

5. OTHER SPACE APPLICATIONS

A gas, nitrous oxide, can be used for cold-gas propulsion. This gives the benefit of possible dual-mode propulsion system for micro-satellite sharing one propellant and providing the spacecraft with all necessary functions to fulfil its mission.

The proposed technique for nitrous oxide decomposition promotes the use of the propellant for hybrid rocket motor and bi-propellant thruster applications. The theoretical performance of some propellant combinations using nitrous oxide in comparison with conventional and alternative combinations are shown in Figure 10.

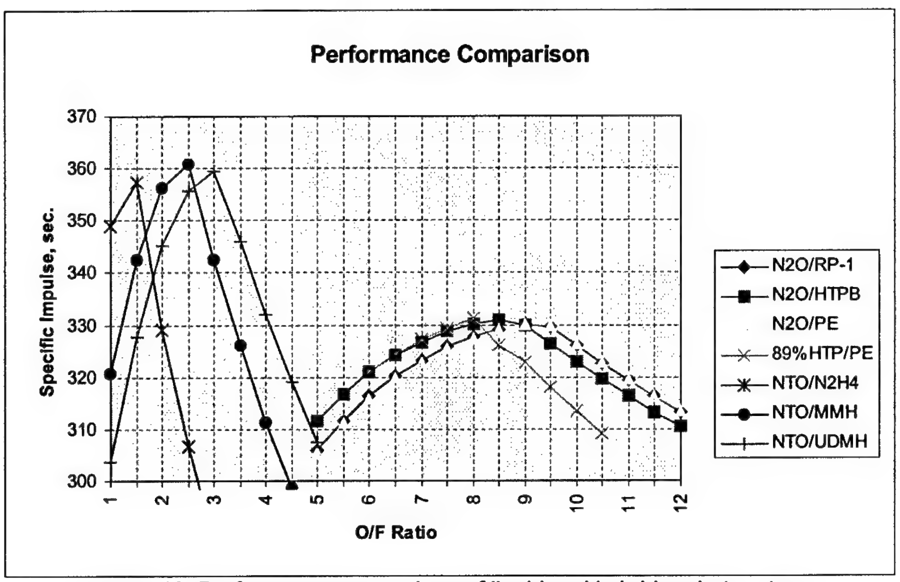


Figure 10. Performance comparison of liquid and hybrid rocket motors.

6. TEST APPARATUS

The schematics of a device for nitrous oxide decomposition is given in Figure 11. In this device a flow of nitrous oxide is injected into the decomposition chamber. Upon injection, nitrous oxide starts to decompose on an electrically heated catalytic wire. The heat generated by decomposition activates the main catalyst coated on a ceramic substrate, which in turn decomposes more nitrous

oxide. The process proceeds with increasing temperature until all of the catalyst is activated and the rate of decomposition reaches its maximum when steady state is achieved. The products of the decomposition leave the chamber through the converging-diverging nozzle generating thrust. Once self-sustaining nitrous oxide decomposition is achieved, the electrical power input is no longer required.

As a first attempt towards the development of flight qualified thruster, a 190mm-piece of 2.54mm-inner diameter stainless steel pipe was adopted to house the catalysts. The test design is shown in Figures 12 and 13.

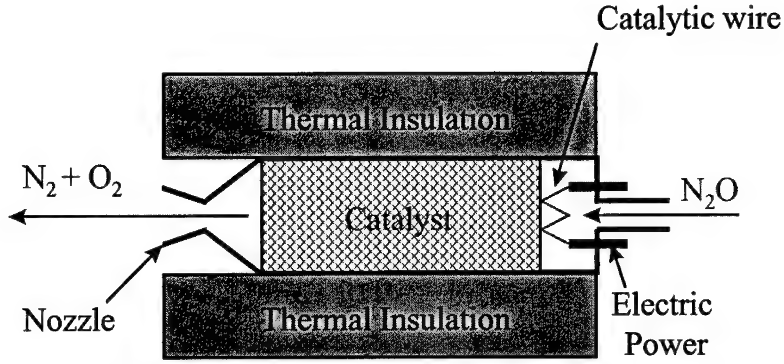


Figure 11. Nitrous oxide mono-propellant thruster schematics.

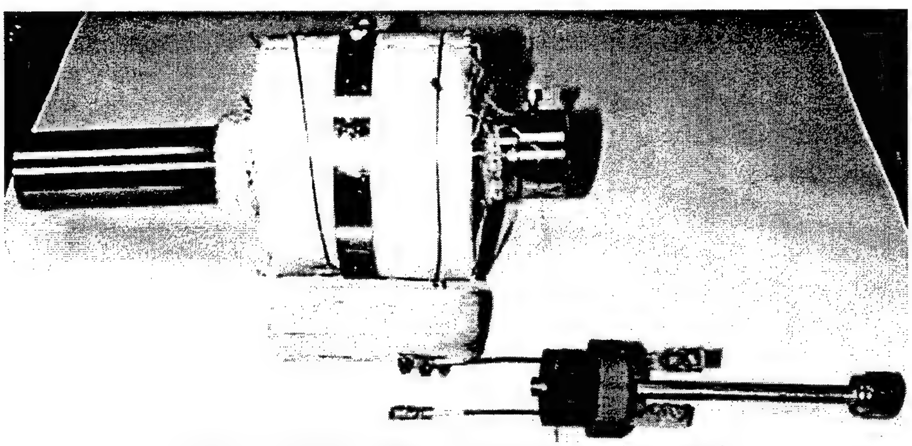


Figure 12. Current nitrous oxide assembly (side view).

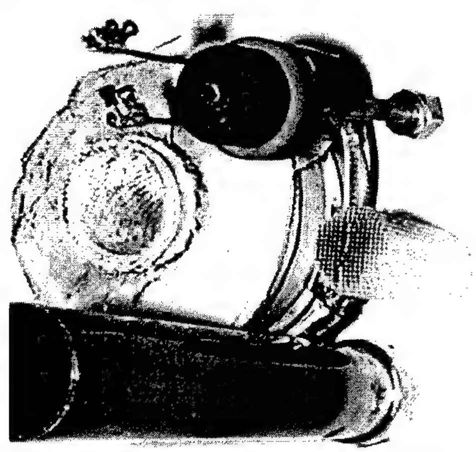


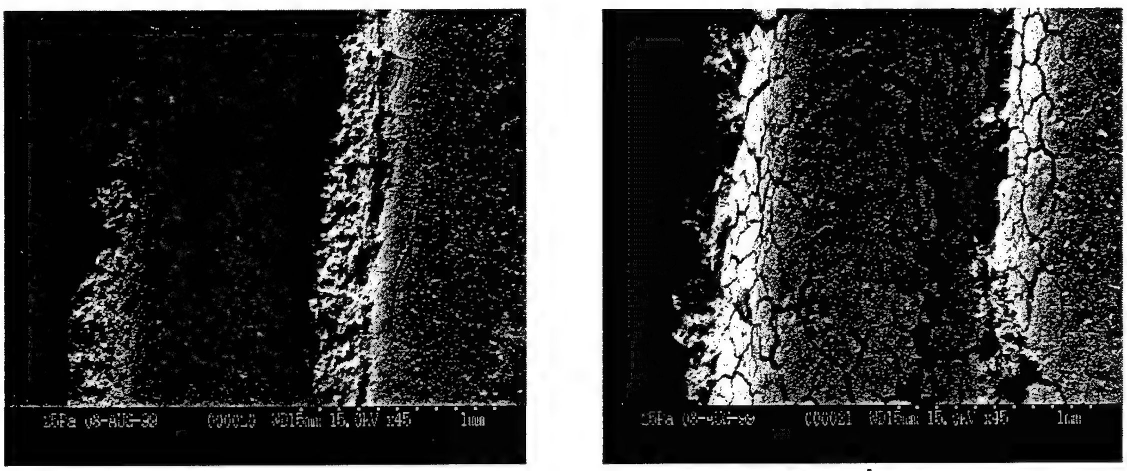
Figure 13. Current nitrous oxide assembly (top view).

7. TEST RESULTS

Ten tests have been accomplished up to date. Self-sustaining catalytic decomposition of nitrous oxide has been repeatedly demonstrated in all tests. Platinum/rhodium catalytic wires have been successfully tested as decomposition initiators. Several different main catalysts were tested including iron coated ceramic honeycomb monolith, rhodium coated ceramic honeycomb monolith, and rhodium coated alumina pellets.

In the case of iron coated monolith the power input varies from 50 to 80W. Catalyst activation temperature is 450°C. Decomposition temperature of nitrous oxide is in excess of 1100°C. This corresponds to 170s specific impulse performance (see Figures 3 & 5). Currently, operating temperature is limited by sintering temperature (~1200°C) of main catalyst washcoat. Nitrous oxide mass flow rates in excess of 1.1 gm/s have been supported.

Power input for rhodium coated monoliths varies from 24 to 32W. Catalyst activation temperature is 300°C. Maximum decomposition temperature is in excess of 1130°C. Alumina coated cordierite matrix can not cope with temperatures above 1000°C. Thermal stresses cause erosion of the monolith surface (see Figure 14). Therefore the catalyst lifetime is very short. Nitrous oxide mass flow rates up to 1.0 gm/s have been supported.

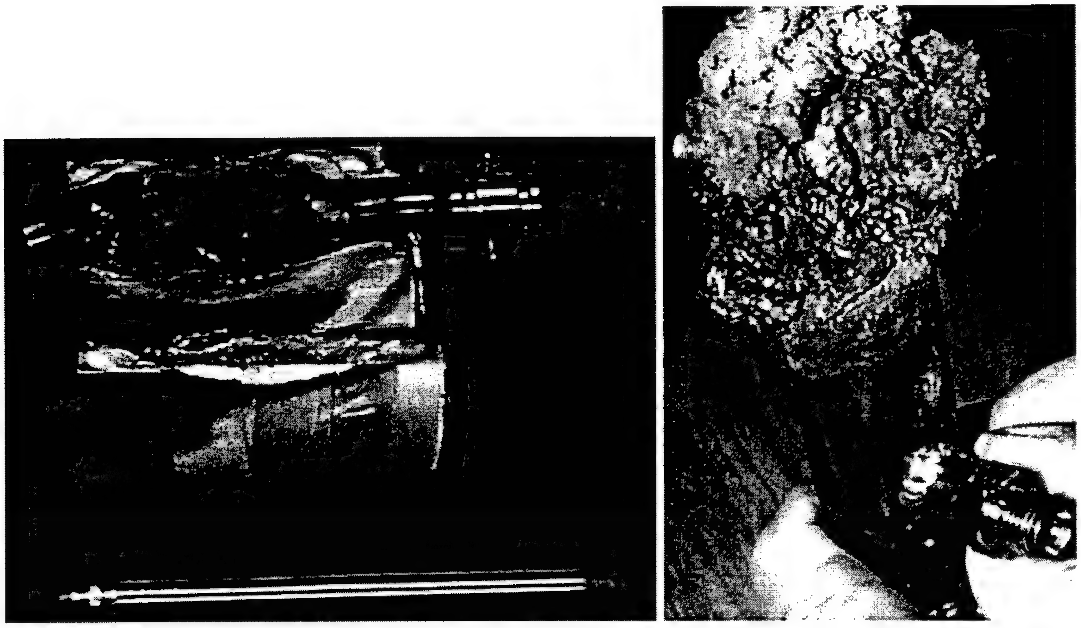


a b

Figure 14. Monolith surface a) before (virgin); and b) after (eroded) test.

Alumina pellets coated with rhodium is a suitable catalyst for nitrous oxide decomposition. Power input varies from 39 to 45W. Catalyst activation temperature is 255°C. Maximum decomposition temperature is in excess of 1130°C. The demonstrated cumulative catalyst lifetime is in excess of 76min. Nitrous oxide mass flow rates in excess of 1.1 gm/s have been supported.

In combination with iron oxide and alumina pellets coated with rhodium the decomposition temperature of nitrous oxide is high enough to melt stainless steel (see Figure 15).



a b

Figure 15. Test design after firing: a) Stainless steel pipe is melted with iron catalyst and micropore thermal insulation; b) Alumina pellets coated by catalyst have survived the heat.

8. TEST PLAN

Test Apparatus

Learning

Maximum Mass Flow Rates

Maximum Achievable Decomposition Temperature

Catalyst Activation Temperature

Start-up time vs. Power Input (wire material, length, & knitting)

Construction Materials (electrical insulation, catalyst substrate ...)

1N Prototype Thruster (sea level)

Performance evaluation

Effect of chamber pressure (different throat sizes)

Optimisation of catalyst pack size (diameter & length)

Optimisation of start-up parameters (input power & flow)

Construction Materials (thermal insulation, nozzle, ...)

Alternative pellet catalysts

Catalyst Lifetime

1N Prototype Thruster (vacuum)

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NITROUS OXIDE AS A ROCKET PROPELLANT FOR SMALL SATELLITES

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ABSTRACT *– Nitrous oxide as a multi-purpose propellant for small satellites is discussed. Potential space applications of this propellant are given. Performance of nitrous oxide in cold-gas, monopropellant, resistojet, and bipropellant thrusters is compared to other conventional and alternative propellants. Surrey's previous experience and achievements regarding the use of this gas for propulsion applications are reported. A multi-mode nitrous oxide propulsion concept is presented and shown to deliver higher performance in comparison to conventional systems. A nitrous oxide catalytic decomposition technique is suggested for restartable spacecraft propulsion. A conclusion describes the long-term feasibility of novel nitrous oxide propulsion option concepts.*

1 – INTRODUCTION

The small satellite industry depends on secondary launch opportunities. The limited number of such opportunities restricts the variety of satellite orbits. Therefore, for a spacecraft to continue to exploit the availability of launches and expand its capability for more ambitious communications, remote sensing and science missions, a propulsion system is required.

There are three main propulsion system functions for satellites:

1. Attitude Control - keeping a spacecraft pointed to the desired direction.
2. Orbit Maintenance (station-keeping) - keeping a spacecraft in the desired mission orbit.
3. Orbit Manoeuvring - moving a space vehicle to another desired orbit.

On larger spacecrafts (>500kg), these needs have been traditionally satisfied by the following system options:

- Cold-gas propulsion – mainly using nitrogen for attitude control
- Hydrazine-based systems – for attitude control, station-keeping and orbit manoeuvring
- Solid rockets – for orbit manoeuvring

However, scaling a satellite down imposes unique integration requirements and constraints for propulsion systems. For example, low specific impulse performance of cold-gas propulsion (typically 60s) aggravated by severe volume constraints (propulsion envelope volume of about 7 litres), limits the range of typical (<75kg) micro-satellite orbital transfer manoeuvres to approximately 5m/s. Hydrazine-based systems rely on highly toxic propellants. This demands elaborate system development and pre-flight safety requirements. To reduce mission life-cycle costs, spacecraft manufacturers would prefer to reduce or eliminate this expense that can be prohibitive for small, university-based missions. Solid rocket motors have similar expensive requirements for safety and handling that also increase their life-cycle costs. In addition, the "single-shot" nature of solids makes them unsuitable for multi-thrust mission requirements. Furthermore, micro-satellite power systems deliver <50W (orbit average) making it difficult to cope with the high power demands

(>100W) associated with off-the-shelf electrostatic and electromagnetic propulsion systems. Thermoelectric systems are feasible. However, total power available and the choice of working fluids both are critical to spacecraft integration and will be addressed later in this paper.

To overcome the inherent limitations of existing propulsion technology for small satellites, recent research at the *University of Surrey* has focused on nitrous oxide (N_2O). Nitrous oxide (known as "laughing gas", dinitrogen oxide, or dinitrogen monoxide) is a colourless, non-toxic, liquefied gas with a slightly sweet taste and odour. It is non-corrosive and may be used with common structural materials. Nitrous oxide is stable and comparatively unreactive at ordinary temperatures. [Brak 80] It is decomposed into nitrogen and oxygen by heating above 520°C. [Dain 96] Furthermore, this decomposition reaction can be accelerated by a catalyst. At elevated temperatures, nitrous oxide supports combustion. It is classified by the U.S. Department of Transportation as a non-flammable, compressed gas and is shipped with the required "Green Label". [Brak 80]

Three basic properties of nitrous oxide make it attractive as a multi-purpose rocket propellant:

- Stored as a liquid (~745kg/m^3) with a vapour pressure of ~51bar (at 20°C)
- Decomposes exothermically with maximum decomposition temperature reaching ~1640°C
- Free oxygen available by decomposition can be combusted with a wide variety of fuels

Taking advantage of these properties space propulsion applications of nitrous oxide may be extended to:

- Cold-gas propulsion for attitude control of a spacecraft
- Monopropellant thruster for spacecraft station-keeping and small orbit manoeuvres
- Hybrid or liquid bipropellant rockets for large orbital manoeuvring

Since the whole range of propulsion functions can be covered by one self-pressurising propellant, multi-mode propulsion systems can be envisioned to satisfy a wide variety mission requirements. Such systems would employ different types of thrusters fed by nitrous oxide from a single, simply designed storage tank. This paper introduces nitrous oxide as a multi-purpose propellant for small satellites.

2 – STORABILITY

To become a feasible option for application, a propellant must be storable on-board a small satellite for the required mission lifetime. Nitrous oxide is a storable propellant that does not require an expulsion system. It can be stored as liquid or compressed gas (above the critical point) through a wide temperature range, limited by thermal decomposition temperature of 520°C [Dain 96] on the upper end and the triple point (-90.8°C) [Brak 80] on the lower end of the scale. The maximum storage temperature limit is dependant on provisioned tank pressure and ullage volume. The practical maximum operational temperature number for designed tank pressure of 200bar would be 60°C. The recommended low operational temperature of -34°C would allow nitrous oxide vapour pressure to stay above 11bar.

Recent experience of storing nitrous oxide on-board the *UoSAT-12* mini-satellite for more than one year indicates that storage of the gas in-orbit is not a problem.

3 – PERFORMANCE COMPARISON

The arguments in favour of nitrous oxide application on small satellites are discussed below by comparing it to conventional and alternative propellants.

3.1 – Cold-gas

Cold-gas propulsion is typically used for spacecraft attitude control because of its small minimum impulse bit. Ten common, easily available gases were selected for comparison. The results of the comparison are presented in fig. 1.

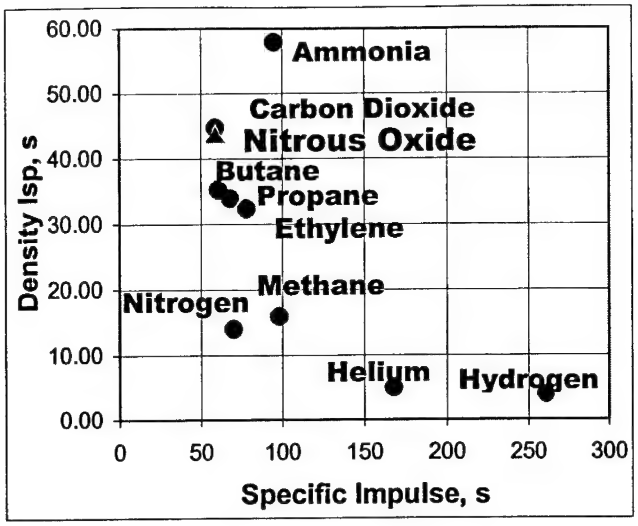


Fig. 1: Theoretical performance comparison of cold-gas propellants. (nozzle expansion ratio = 200)

Although nitrous oxide (along with carbon dioxide) provides the lowest theoretical specific impulse it has the second highest storage density amongst the selected cold-gas propellants. Therefore, it is able to deliver a higher change in total spacecraft velocity per unit volume of propellant (i.e. density Isp) than butane, propane, ethylene, methane, nitrogen, helium and hydrogen, all of which provide higher specific impulses but lower densities. Denser propellants are preferable for small satellites, which are volumetrically constrained by launch requirements as secondary payloads. Nitrous oxide has the third highest density Isp after ammonia and carbon dioxide. Ammonia, however, is a toxic, highly reactive chemical that in combination with air may present an explosion hazard. Ammonia is incompatible with copper, tin, zinc and their alloys. Due to its high triple point, carbon dioxide may solidify in the feed lines and requires a thermal control system. Conversely, nitrous oxide is non-toxic, non-flammable; it has a low triple point and is compatible with common structural materials.

3.2 – Monopropellants

Recent achievements in development of nitrous oxide decomposition catalysts for automotive industry have made nitrous oxide monopropellant applications feasible. Theoretical specific impulse of such a thruster is evaluated using the *USAF ISP* computer code written by Curt Selph. The result of the computation is shown in fig. 2. The specific impulse monotonically rises with increasing decomposition temperature until it reaches its maximum at about 1640°C.

The performance of nitrous oxide monopropellant was compared with that of hydrogen peroxide and conventional hydrazine thrusters. (see table 1) The results reveal that a nitrous oxide monopropellant thruster is capable of moderate theoretical specific impulse performance, 16% lower than that of hydrazine but 15% higher than that of hydrogen peroxide thrusters. Each of these propellants can be stored on board spacecraft. Although storage density of liquefied nitrous oxide is 26% lower than that of hydrazine and 45% lower than that of hydrogen peroxide, the low vapour pressure of these two propellants requires the use of a separate propellant expulsion system.

The storage temperature range of nitrous oxide is discussed earlier in this paper. In general, this range is broader than that of hydrogen peroxide and hydrazine. Storage temperature ranges for hydrogen peroxide vary as a function of its concentration. For the case of 89% strength hydrogen peroxide the low temperature limit is defined by a freezing point of -12°C. Five-degree margin between low operational limit and freezing point is a precaution against formation of slush. A similar estimate is applied to hydrazine that has a freezing point of about 2°C. Although the boiling temperature of hydrogen peroxide is 141°C, the strong temperature

dependence of its decomposition rate [JANN 84] limits the storage temperature to below 38°C. For hydrazine the upper storage temperature is limited to 40°C although the boiling point is 113°C.

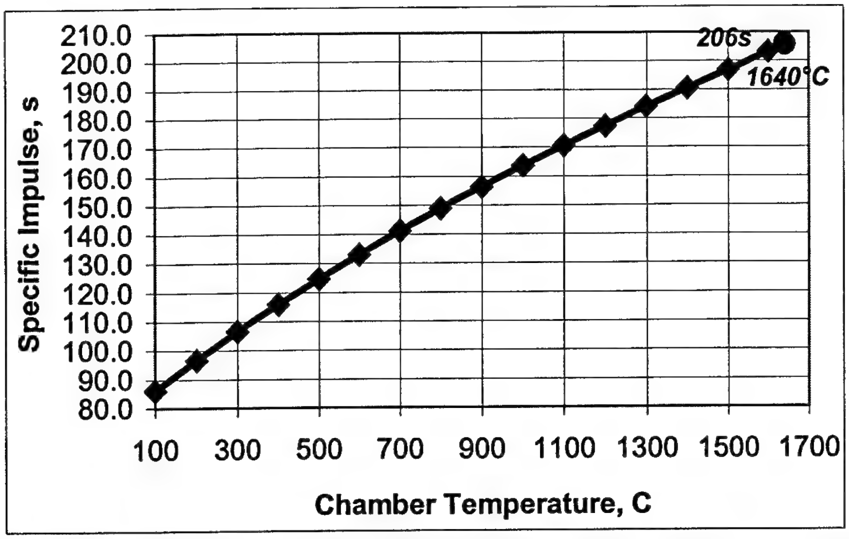
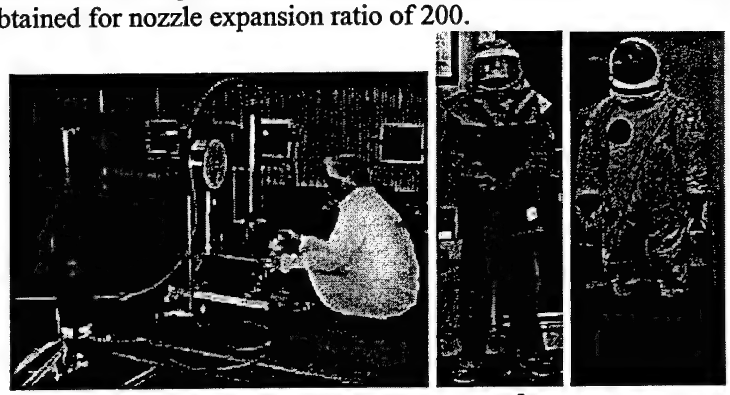


Fig. 2: Theoretical specific impulse of nitrous oxide monopropellant thruster as a function of chamber temperature (chamber pressure = 3bar; nozzle expansion ratio = 200).

TABLE 1: Properties of selected monopropellants.

Propellant	**Nitrous Oxide**	**Hydrogen Peroxide**	**Hydrazine**
Chemical Formula	N_2O	H_2O_2	N_2H_4
Specific Impulse (theoretical), s	206	179	245
Storability	Storable	Storable (decomposes)	Storable
Storage Density, kg/m³	745 @ 21°C 52.4 bar	1347	1004
Vapour pressure	50.8bar @ 20°C	0.00345bar @ 20°C	0.0214bar @ 26.7°C
Storage Temperature Range, °C	-34—60	-7—38	9—40
Toxicity	Non-toxic	Burns skin	Very Toxic
Flammability	Non-flammable	Non-flammable	Flammable
Flight Heritage	feed system UoSAT-12	flown	flown

Notes: All propellants are stored in liquid state. Hydrogen peroxide is 89% strength. Theoretical specific impulse data obtained for nozzle expansion ratio of 200.



a **b** **c**

Fig. 3: Protective handling equipment:
a) *UoSAT-12* Nitrous Oxide loading;
b) Chemical boiler suit for Hydrogen Peroxide handling;
c) *SCAPE* suits for Hydrazine and Nitrogen Tetroxide operations

In addition to raw performance, propellant handling is another significant issue to consider. Nitrous oxide handling requires minimal safety equipment (fig. 3a), while splash protection is necessary for hydrogen peroxide (fig. 3b). Complete protection is essential for hydrazine handling (fig. 3c). Nitrous oxide presents no fire or explosion hazard, while hydrogen peroxide may spontaneously ignite on contact with hydrocarbons. Contaminated hydrogen peroxide is unstable and presents a serious explosive hazard. High fire and explosion hazards are associated with hydrazine.

Although a nitrous oxide monopropellant thruster has yet to be flown, the feed system is currently under test on-board the *UoSAT-12* mini-satellite. Hydrogen peroxide monopropellant thrusters were employed on the number of missions. [McCo 65, Sell 96, Whit 98] Presently, hydrazine monopropellant thrusters are an extensively used space technology. [Sutt 92]

3.2.1 - *Decomposition*

A catalytic decomposition technique is suggested for a nitrous oxide monopropellant thruster. Inside the thruster, nitrous oxide decomposes according to the reaction equation:

$$N_2O(g) \rightarrow N_2(g) + \tfrac{1}{2}O_2(g) \qquad (\Delta H^{\circ}_R = -82.05\ \mathrm{kJ/mole}) \qquad \text{[Atki 97]}$$

The reaction generates hot oxygen-rich mixture. Once the heat balance is achieved, this exothermic reaction becomes self-sustaining.

In general nitrous oxide can be decomposed thermally, for example, in a resistojet. Thermal decomposition, however, requires high power input. The activation energy barrier for nitrous oxide is about 250kJ/mole [Atki 97]. Therefore, in order to attain the required rates of thermal decomposition, the gas must be heated to above 1000°C.

A catalyst lowers the activation energy barrier. Thus, the decomposition occurs at much lower temperatures. Another advantage of catalytic decomposition is that once the catalyst is heated to activation temperature, the power input is no longer required to support the process. Therefore, the use of a catalyst leads to significant power savings over thermal decomposition technique employed in a resistojet. This approach makes nitrous oxide propulsion a feasible option for small satellites, extending its application range from mini-satellite (100-500kg) to micro-satellite (10-100kg) platforms.

3.2.2 – *Results*

The potential for nitrous oxide catalytic decomposition technique has been demonstrated in dozens of experimental tests at Westcott test facility of *Surrey Space Centre* (U.K.). During these tests:

- The proof-of-concept was demonstrated.
- Repeatable, self-sustaining, decomposition of nitrous oxide has been achieved using different catalysts.
- Hot restarts at zero-power input have been repeatedly shown in operation.
- More than 50 different catalysts have been tested.
- A catalyst activation temperature as low as 250°C has been recorded.
- Nitrous oxide mass flow rates above 1.1gm/s have been supported.
- Decomposition temperatures in excess of 1500°C have been demonstrated.
- Electrical power input as low as 24W has been used.
- The time required to heat the catalyst from ambient to activation temperature has been as short as 3min.
- A catalyst lifetime in excess of 76min. was demonstrated.

Despite these achievements, the problems associated with high temperature (>1100°C) instability of the catalyst materials remain. Although the existing catalysts work well, high-temperature stable catalyst materials would enhance the performance of a monopropellant thruster. The detailed report regarding nitrous oxide catalytic decomposition research at Surrey will be presented in future publications.

Current research at Surrey is focused on development of nitrous oxide monopropellant thrusters and high-temperature decomposition catalysts.

3.3 – Resistojets

Heating a propellant in a resistojet improves specific impulse performance in comparison with cold-gas thrusters. Due to low heat transfer rates, resistojets are preferable for long duration firings. Therefore, orbit maintenance (or station-keeping) is a suitable function for such a thruster. Since power is the major constraint for electric thrusters on small spacecraft, specific impulse of several resistojet propellants is compared (in fig. 4) by consumed energy. From that perspective, an *"ideal"* resistojet propellant for a small spacecraft would deliver the highest specific impulse at minimum input power. Therefore, it would locate itself towards top left corner of the figure. In this figure, a curve for more efficient propellant would be steeper then that of for a less efficient one. Ordinate axis of the graph corresponds to zero-power operational modes. Two of such modes are possible, when a resistojet is run as a cold-gas system, and when the heat generated as a result of initiated self-sustaining exothermic decomposition reaction is used. This latter feature can be described as a monopropellant mode.

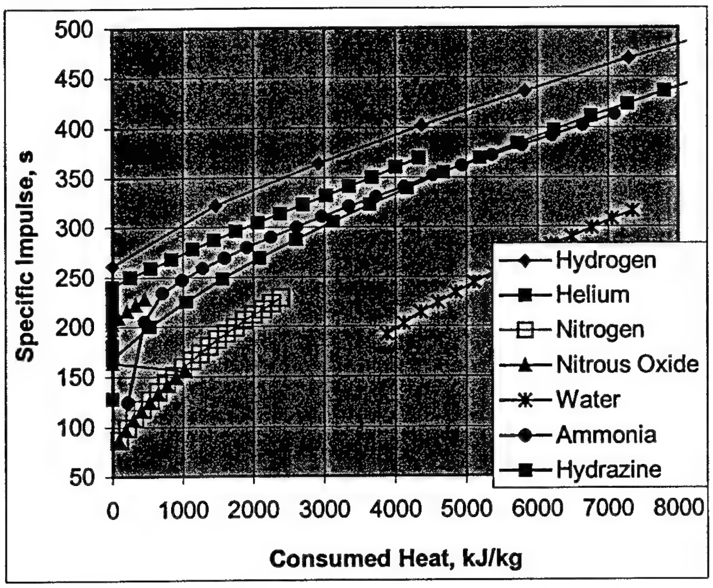


Fig.4: Theoretical performance comparison of resistojet propellants: specific impulse vs. heat required for heating propellant to the process temperature.

From this figure, hydrogen is a good propellant because its basic high specific impulse grows fast with only little additional heating. However, its low density violates volumetric constraints for small satellite discussed earlier. The next best option would appear to be hydrazine.

Nitrous oxide resistojet is a special case. From the start, its performance almost overlaps that of nitrogen resistojet until self-sustaining decomposition is initiated. At that point, power input can be turned off, and the thruster will continue to operate as a monopropellant. Since the maximum temperature of nitrous oxide decomposition (~1640°C) is high, heating of its reaction products in resistojet is impractical due to the challenging choice of high temperature construction materials. Thus, the practical temperature operating range for nitrous oxide resistojet coincides with that of a monopropellant described above. The power savings associated with nitrous oxide catalytic decomposition in a monopropellant, however, support its use instead of resistojet.

On the whole, the specific impulse that can be delivered by hydrazine resistojet is higher than that of nitrous oxide resistojet or monopropellant. However, hydrazine toxicity and higher powers (>100W) required for

such a resistojet might become the prohibitive drawbacks for small satellite applications. In this case, non-toxic nitrous oxide resistojet or monopropellant operating at zero-power mode are desirable.
The work on low-power resistojets started at Surrey by Timothy Lawrence in 1995. [Curi 99, Lawr 98, SSTL] Since then:

- The highest recorded specific impulse of the *Mark-III* nitrous oxide resistojet was 148s.
- During vacuum test of the *Mark-III* resistojet at the US Air Force Research Lab at *EDWARDS* Air Force Base, CA, a self-sustaining decomposition was observed for longer than 18 hours.
- The first (0.1N and 100W) nitrous oxide resistojet thruster *Mark-IV* has been successfully commissioned on board the *UoSAT-12* mini-satellite with 2 firings on 27 July 1999 and 11 April 2000 from a 700 km orbit. Discussion of these flight results will be presented in future papers.

3.4 – Bipropellants

A hot nitrogen-oxygen mixture generated by nitrous oxide decomposition can be used to combust a fuel. Therefore, bipropellant thrusters employing nitrous oxide as an oxidiser are feasible.
Theoretical performance of several nitrous oxide bipropellant combinations has been evaluated to determine their feasibility for future applications. The consideration criteria are:

- Storability in orbit
- Density Isp (volumetric constraint for small satellites)
- Specific impulse
- Toxicity
- Availability and low cost

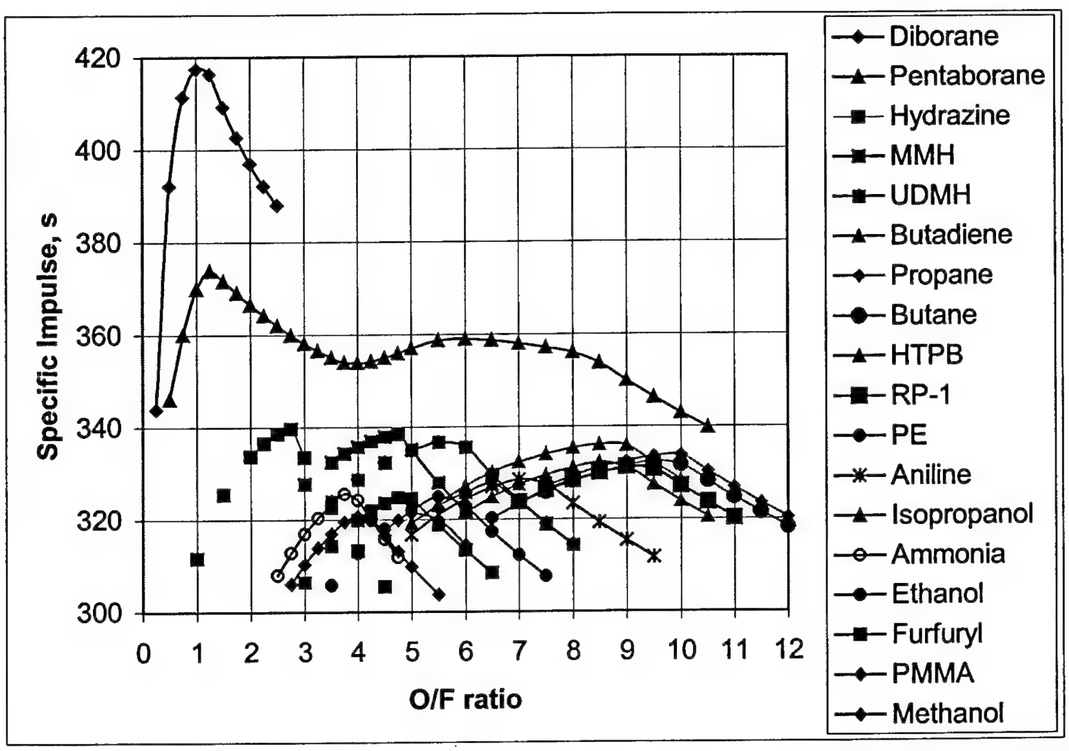


Fig. 5: Theoretical performance of nitrous oxide/fuel propellant combinations. (O/F – oxidiser-to-fuel)

The results of the analysis are presented in figs. 5, 6, and table 2. Toxic boranes and hydrazine family fuels deliver remarkable performance when combusted with nitrous oxide. However, toxicity and other safety factors can significantly raise the total cost of a given mission. For some missions, especially very low-cost

ones such as those undertaken within a University environment, the increased mission safety "overhead" required by the use of these propellants can increase the total system cost to point that the mission is no longer feasible. [Sell 98] For this reason these fuels along with aniline currently are not considered for small satellite applications.

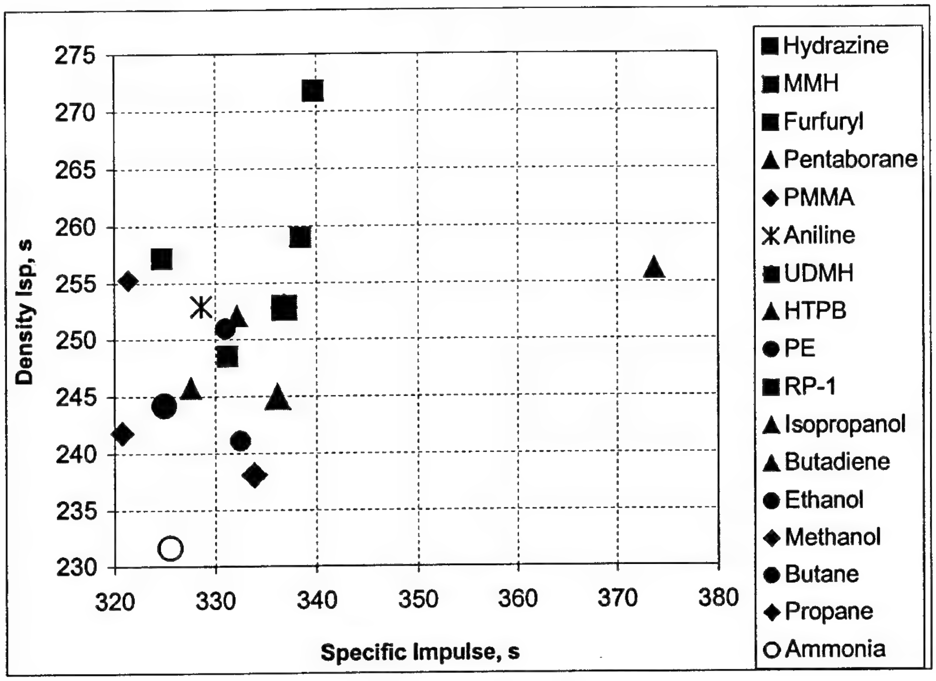


Fig. 6: Theoretical performance of nitrous oxide bipropellants.

Non-toxic plastics (HTPB, PE, and PMMA) along with kerosene deliver moderate performance, are easily available, and inexpensive. Of these, HTPB provides better performance; polyethylene might be preferable due to its ease of being machined; kerosene might be used in liquid rocket engine; PMMA has higher density but delivers lower specific impulse.

Flammable liquefied gases (butadiene, butane, propane) deliver only slightly higher specific impulse performance than non-toxic plastics and kerosene but are less dense. The associated fire hazard, however, would require more careful consideration raising the total system cost. On the whole, they are recommended for small satellite applications.

The performance of alcohols, except furfuryl one, and ammonia are lower than the performance of non-toxic plastics and kerosene. Therefore, they are not preferable fuel options at present. Furfuryl might be employed when tighter satellite packaging is required.

In general, the variety of fuel combinations with nitrous oxide is more numerous. Bowman [Bowm 50] gave theoretical performance examples for some common and exotic fuels. Most of them can be considered as currently impractical for small satellite applications. Gardner [Gard 42] recommended carbon disulfide (CS_2) as "the most practical fuel" for use with nitrous oxide. This combination gives high theoretical combustion temperature. Although liquid carbon disulfide has high storage density (1255kg/m^3 at 20°C), it is highly toxic and flammable. Therefore, at present it is unfeasible on a small satellite.

Overall, the comparison reveals that HTPB, PE and RP-1 are three the most practical fuels for nitrous oxide bipropellants on small satellites and upper-stages.

In fig. 7, the performance of these three is compared to conventional propellant combinations. Although the theoretical performance of the non-toxic bipropellants is somewhat lower than that of highly toxic conventional nitrogen tetroxide/hydrazine family propellant combinations it is still high enough (330s) to be considered for small satellite applications.

TABLE 2: Fuels for use with nitrous oxide

Name	Alternative Names	Storability	Flammability	Toxicity	Availability	Cost	Remarks
Ammonia	Anhydrous ammonia	l/g	N	T	E	L	Corrosive
Aniline	Aniline oil; aminobenzene; phenylamine	l	N	T	A	M	non-corrosive
Butadiene	1,3- Butadiene	l/g	F	L	E	L	non-corrosive
Butane	n-Butane	l/g	F	L	E	L	non-corrosive
Diborane	Diboron hexahydride; boroethane	g	F	H	D	H	Cryogenic; unstable
Ethanol	Ethyl alcohol; grain alcohol	l	N	L	E	L	
Furfuryl	Furfuryl alcohol	l	N	L	E	L	
HTPB	Hydroxyl-Terminated Polybutadiene; Rubber	s	N	N	E	L	Easily Cast
Hydrazine		l	F	T	A	H	
Isopropanol	Isopropyl alcohol	l	N	L	E	L	
Methanol	Methyl alcohol; wood alcohol	l	N	L	E	L	
MMH	MonoMethyl Hydrazine	l	F	T	A	H	
PE	Polyethylene	s	N	N	E	L	Easily Machined
Pentaborane	Pentaboron; ennahydride; pentaborane-9	l	F	H	D	H	
PMMA	Poly-Methyl Methacrylate	s	N	N	E	L	Easily Machined
Propane	dimethylmethane	l/g	F	N	E	L	
RP-1	Rocket Propellant; Kerosene	l	F	N	E	L	
UDMH	Unsymmetrical DiMethyl Hydrazine	l	F	T	A	H	

Notes: s – solid; l – liquid; g – gas; F – flammable; T – toxic; N – non-flammable, non-toxic; A – available; E – easy; D – difficult; L – low; M – medium; H – high.

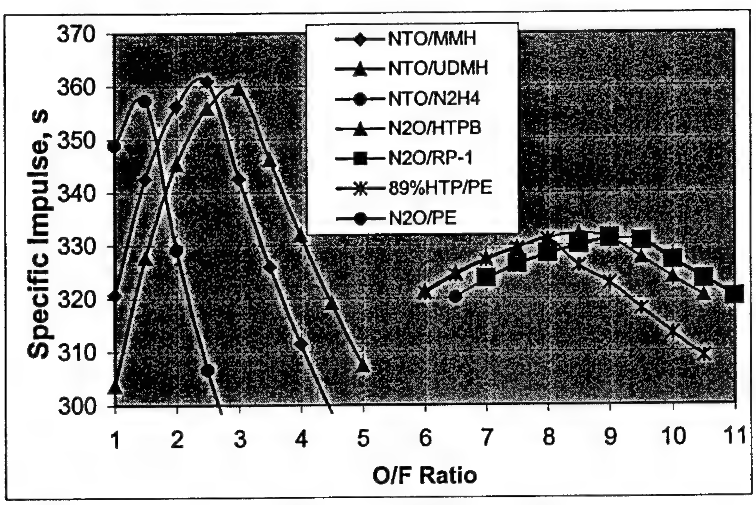


Fig. 7: Theoretical performance of bipropellant combinations using nitrous oxide as an oxidiser. The performance is calculated by USAF ISP computer code. (N2H4 – Hydrazine; N2O – Nitrous Oxide; NTO – Nitrogen Tetroxide)

Nitrous oxide has already been used in bipropellants. A small research motor called *Hecht* developed by the Germans used nitrous oxide in combination with aqueous methyl alcohol (28% methanol) fuel. [Noeg] American Rocket Company (*AMROC*) used nitrous oxide as an oxidiser in its hybrid rocket motors. [SDHR

00] Presently nitrous oxide is used in amateur rocketry in combination with solid (polypropylene, HTPB, asphalt, etc.) and liquid (alcohols, etc.) fuels. [AIIR, Fink 98, FTSO 97, McGa, RATT] The Space Cruiser System, a fully recoverable and reusable piloted passenger carrying sub-orbital 2-stage space-plane, is proposed on using three nitrous oxide/propane pressure fed, rocket engines.
None of these applications, however, were provisioned for in orbit start-up and restart. Meanwhile, start-up in vacuum and in the micro-gravity environment is not a trivial task, and restartability is an essential feature for spacecraft propulsion when more than one in-orbit manoeuvre is required.
The technique for nitrous oxide decomposition investigated at the University of Surrey further promotes the use of the gas in bipropellants for restartable spacecraft upper-stages since it has been shown to ignite solid fuel (PMMA). A vortex flow "pancake" hybrid rocket motor was successfully ignited by injection of hot gaseous products of nitrous oxide decomposition into the combustion chamber. [Haag 00] In the test, a well-known hydrazine decomposition catalyst (*Shell 405*) was used to decompose nitrous oxide.

3.5 – Multi-Mode Propulsion Systems

Nitrous oxide may be used as a propellant for multi-mode propulsion system. For advanced small satellite missions multi-mode propulsion system operations are essential. Looking at the performance values for individual system applications of nitrous oxide, one may not be convinced of benefit. However, when an integrated system approach is taken, considering the varied propulsion requirements during a typical mission, the versatility of nitrous oxide make it a compelling choice.
Simple dual-mode cold-gas/monopropellant propulsion (fig. 8) is taken out of a variety of possible multi-mode systems as an example to illustrate advantages of nitrous oxide propellant applications. The results of the comparison summarised in fig. 9 show that:

- Starting at the point when velocity change by cold-gas propulsion is ~7% of total spacecraft velocity change, nitrous oxide propellant storage system is more compact than that of hydrazine monopropellant/nitrogen cold-gas;
- Starting at the point when velocity change by cold-gas propulsion is ~13% of total spacecraft velocity change, nitrous oxide propulsion system is lighter than that of hydrazine monopropellant/nitrogen cold-gas;
- The both parameters improve with increasing cold-gas propulsion fraction.

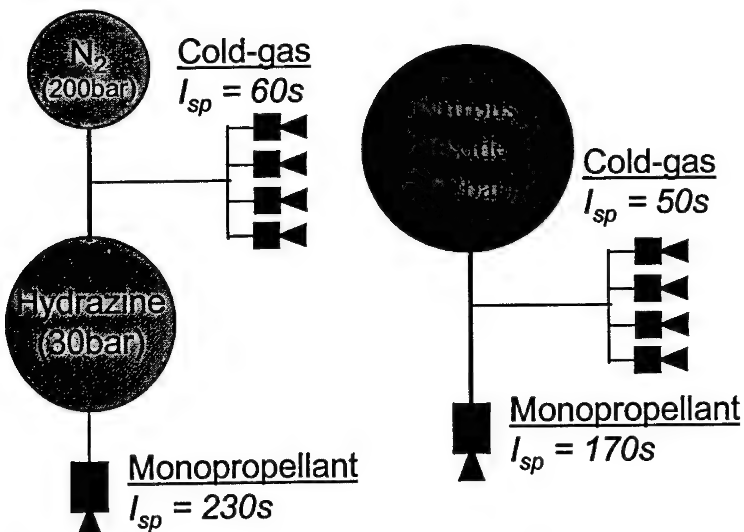


Fig. 8: Schematics of dual-mode propulsion system options for small satellite.

In addition, non-toxic nitrous oxide system is of simpler design than that of using toxic hydrazine propellant.

Furthermore, in the case of nitrous oxide system the propellant may be used till depletion by either mode with no restrictions except provision required for total spacecraft velocity change. Meanwhile, in the case of hydrazine, margins for use of the propellants by each mode must be imposed. Hence, application of nitrous oxide system would give an important advantage of the flexibility in firing strategy during a mission. Therefore, since the propulsion requirements are more relaxed for nitrous oxide systems the number of firings considered in orbit mission scenarios can be increased. This feature is important especially for a spacecraft launched as a secondary payload since launch itself is often undefined until a few months to the launch date.

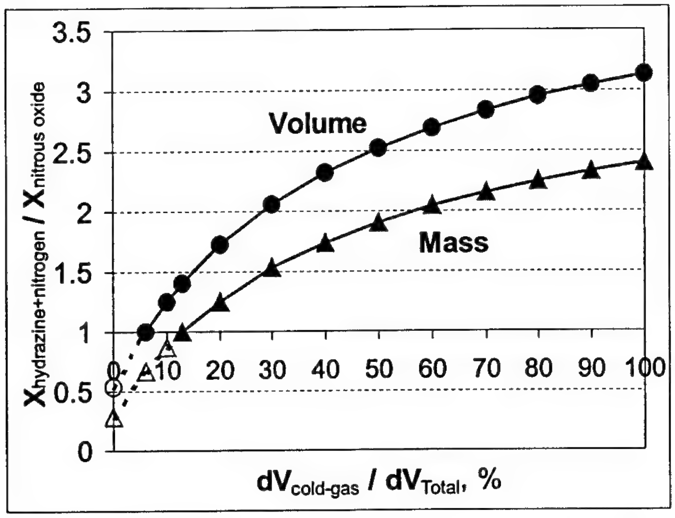


Fig. 9: Performance comparison of hydrazine monopropellant/nitrogen cold-gas to nitrous oxide monopropellant/cold-gas dual-mode propulsion. (**dV** – spacecraft velocity change; **X** denotes propulsion mass or volume respectively)

4 – CONCLUSIONS

Nitrous oxide is a promising propellant for future low cost, small satellite missions. The research regarding application of this gas as a rocket propellant for small satellites is currently under way at Surrey Space Centre.

The experience obtained shows that:

- It can be stored/operated in orbit.
- It can be decomposed on a catalyst.
- The decomposition generates heat and thrust.
- Self-sustaining nitrous oxide decomposition is achievable.
- Generated hot exhaust can ignite fuel upon contact.

Therefore, nitrous oxide cold-gas, monopropellant, resistojet, and bipropellant thrusters are feasible.

The results of performance comparison of these systems show the application of nitrous oxide:

- Dense, liquefied gas for cold-gas propulsion is beneficial for volume-constrained small satellites.
- Resistojet is beneficial for power-constrained small satellites.
- Monopropellant and bipropellant will reduce major "safety overheads".
- Multi-mode systems will be more effective over conventional single-mode alternatives.

The following advantages of nitrous oxide multi-mode propulsion offer:

- Higher total spacecraft velocity change performance over conventional single-mode alternatives.
- Spacecraft power budget reduction.
- Design simplicity.
- Ease of packaging and integration on spacecraft.

- Firing strategy flexibility.
- Increased number of mission scenarios and launch opportunities.
- Reduction in propulsion system cost.

To develop nitrous oxide multi-mode propulsion further research is required in:

- Catalytic decomposition for monopropellant thruster application.
- Bipropellant combustion.
- High-temperature stable catalyst materials.

The research will lead to the development of low cost propulsion system for small satellites.

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Surrey Research on Nitrous Oxide Catalytic Decomposition for Space Applications

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Abstract. Nitrous oxide is introduced as a rocket propellant for small satellites. The reasons for using this propellant on small spacecrafts are discussed. Potential space applications of nitrous oxide are listed. A nitrous oxide catalytic decomposition technique is suggested for restartable spacecraft propulsion. Theoretical performance of a nitrous oxide monopropellant thruster is shown. Basics of nitrous oxide catalytic decomposition are given. Operating principles of a nitrous oxide monopropellant thruster are described. The design of the test apparatus and the set-up for nitrous oxide decomposition are given. Up-to-date achievements of nitrous oxide decomposition research at Surrey are reported. Future design features of nitrous oxide monopropellant thrusters are discussed. A conclusion about future research on nitrous oxide catalytic decomposition is given.

Introduction

Advanced communications, remote sensing and science missions require propulsion for small satellite attitude control, station-keeping and orbit manoeuvring. Launched as secondary payloads, small satellites are subjects of unique propulsion system integration requirements and constraints. Volumetric constraints, for example, make the use of nitrogen for conventional cold-gas propulsion inefficient due to low non-liquefied gas storage density. The electric power constraint (an average of <50W per orbit) restricts application of existing electric propulsion on board small spacecraft. The high cost of conventional mono- and bipropellant systems is usually prohibitive for these low-cost spacecrafts. Since toxic and flammable liquid or explosive solid propellants are involved, substantial conventional propulsion cost reduction is unlikely. In addition, dominating heat losses out of reaction chamber and flow friction losses in the nozzle throat lower performance of conventional thrusters at the low thrust levels of interest (<1N). Moreover, propulsion dry mass fraction increases upon scaling the system down. This often makes integration of compound propulsion on board small spacecraft unfeasible. Therefore, novel approaches are required for efficient small satellite propulsion.

One of the approaches is an application of new propellant. Nitrous oxide has been identified as such a propellant at the University of Surrey. This gas is a non-toxic chemical, stable at normal conditions, and compatible with common structural materials. It can be stored as a liquid or compressed gas through the wide temperature range theoretically limited by its triple point (-90.8°C) [1] on the lower and thermal decomposition temperature (520°C) [2] on the upper end of the scale. However, the recommended practical storage temperature range is from -34 to 60° C. It will be discussed in detail in future publication. [3] Storage density of this liquefied gas is ~745kg/m^3 at 20°C while its vapour pressure is about 52bar. Nitrous oxide decomposes exothermically with adiabatic decomposition temperature reaching ~1640° C. The decomposition can be accelerated by a catalyst. Free oxygen available by nitrous oxide decomposition can be combusted with a wide variety of fuels.

Therefore, nitrous oxide can be used for wide range of space power and propulsion devices including:

- cold-gas thrusters
- monopropellant thrusters
- resistojets thrusters
- bipropellant thrusters
- gas-generators
- turbine drives
- source of breathing oxygen for spacecraft emergency life-support

Thus, it is possible to design a simple, multi-mode propulsion system using this self-pressurising propellant and capable of all necessary functions for successful mission accomplishment. Total dry mass fraction for such a system will be lower in comparison to an alternative system combining conventional propulsion. Since different function type thrusters share the same propellant, the flexibility in the firing strategy is gained in orbit. This important advantage leads to relaxed spacecraft velocity change requirements for each particular propulsion function. Therefore, the number of mission scenarios may be increased. The further advantages of nitrous oxide propulsion are discussed in recent publication. [4]

Recent experience of storing nitrous oxide on-board the *UoSAT-12* mini-satellite for more than one year indicates that:

- Storage of the gas in-orbit is not a problem
- No expulsion system is required
- Minimum safety overheads and application of common materials for system design both provide a potential for low-cost system

To employ nitrous oxide as a rocket propellant it is suggested to take advantage of its catalytic decomposition.

Decomposition

Nitrous oxide catalytic decomposition is considered at Surrey as a key-technology for mono- and bipropellants restartable in orbit.

In the past nitrous oxide decomposition has been extensively studied, both in the presence, and in the absence, of catalysts. [5-38]

The decomposition of nitrous oxide results in formation of nitrogen and oxygen according to the following reaction equation:

$$N_2O(g) \rightarrow N_2(g) + \tfrac{1}{2}O_2(g) + \text{Heat}$$

At standard conditions this exothermic reaction generates ~82kJ of heat per mole of nitrous oxide. [39, 40] However, heat input is required to initiate the reaction. In the case of thermal decomposition the activation energy barrier for nitrous oxide is about 250kJ/mole. [40] Therefore, in order to attain the required reaction rates, the gas must be heated to above 1000°C.

A catalyst lowers the activation energy barrier, and thus the decomposition occurs at much lower temperatures (>200°C). Figure 1 illustrates the advantage of catalytic over thermal decomposition. Textbooks on catalysis and chemisorption often give nitrous oxide decomposition as an example followed by list of catalysts. [41-44]

In the gas flow, if balance between rates of heat generated by decomposition and heat dissipated into surrounding is achieved ($Rate_{heat\ generated} - Rate_{heat\ dissipated} = 0$) then the reaction becomes self-sustaining.

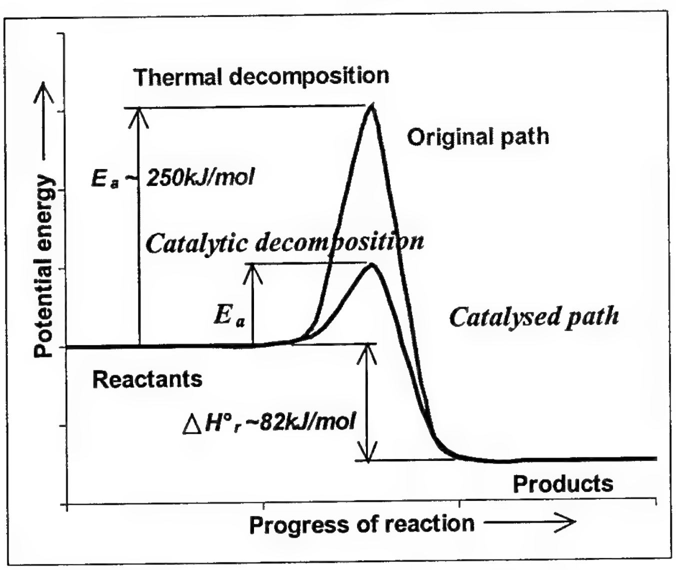


Figure 1. Nitrous oxide decomposition. (E_a – activation energy; ΔH°_r – reaction enthalpy)

Previous Accomplishments

The research on nitrous oxide decomposition started at Surrey after self-sustaining decomposition was first reported by Timothy J. Lawrence in 1998. Earlier that year a self-sustaining nitrous oxide decomposition was observed in the *Mark-III* resistojet for longer than 18 hours during its vacuum test at the US Air Force Research Lab at *EDWARDS* Air Force Base, CA. The highest recorded specific impulse of that nitrous oxide resistojet was 148s. [45, 46] In 1999 the first (0.1N and 100W) nitrous oxide resistojet thruster *Mark-IV* has been successfully commissioned on board the *UoSAT-12* mini-satellite.

Monopropellant Thruster Concept

The schematics of a nitrous oxide monopropellant thruster employing catalytic decomposition is shown in Figure 2. In this device a flow of nitrous oxide is injected into the decomposition chamber. Upon injection, nitrous oxide starts to decompose on an electrically heated catalytic wire. The heat generated by decomposition activates the main catalyst, which in turn decomposes more nitrous oxide, and generates more heat. The process proceeds with increasing temperature until all of the catalyst is activated and the rate of decomposition reaches its maximum when steady state is achieved. This takes a few seconds. The products of the decomposition leave the chamber through the converging-diverging nozzle generating thrust. Once self-sustaining nitrous oxide decomposition is achieved, the electrical power input is no longer required.

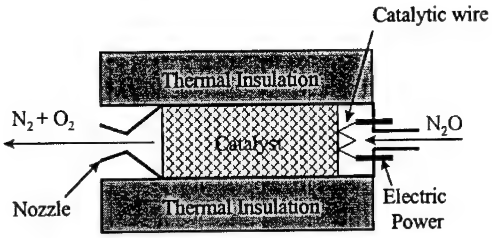


Figure 2. Nitrous oxide monopropellant thruster schematics.

The suggested concept offers significant electrical power savings because:

- It makes use of catalytic decomposition providing considerable input power savings for reaction initiation over thermal decomposition technique employed in a resistojet
- It takes an advantage of self-sustaining decomposition as zero input power main operation mode for a thruster

This is expected to make nitrous oxide propulsion a feasible option for small satellites, extending its application range from mini-satellite (100-500kg) to micro-satellite (10-100kg) platforms.

In Figure 3 theoretical specific impulse performance of nitrous oxide monopropellant thruster was evaluated as a function of chamber temperature using the *USAF ISP* computer code written by Curt Selph. The specific impulse rises monotonically till it reaches value of 206s corresponding to maximum thermodynamic decomposition temperature.

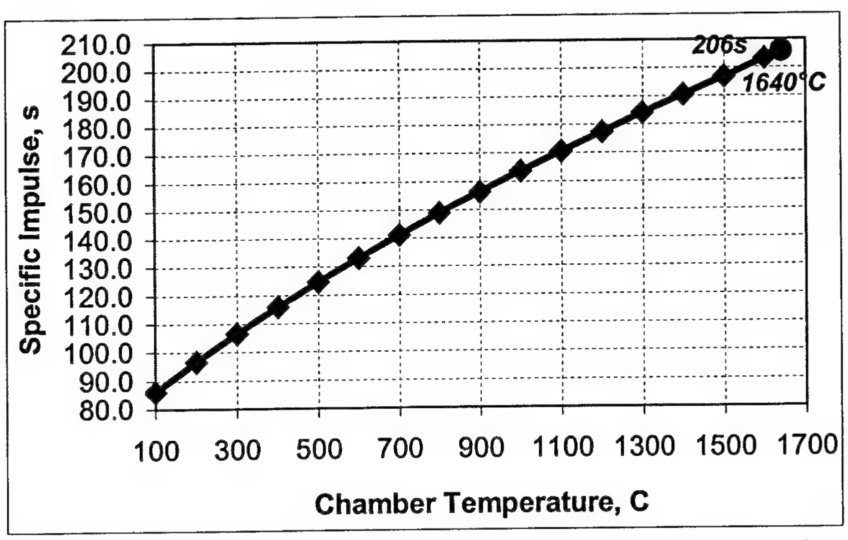


Figure 3. Theoretical specific impulse of nitrous oxide monopropellant thruster as a function of chamber temperature (chamber pressure = 3bar; nozzle expansion ratio = 200).

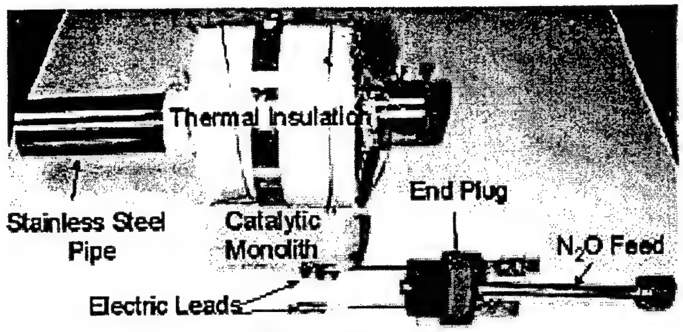


Figure 4. Test design.

Since low thrust levels (<1N) and, thus, low propellant mass flow rates (<0.5gm/s) are of interest, it is suggested to reduce thruster's operating chamber pressure to below 3bar. The lower chamber pressure is desirable for several reasons:

- The famous Le Chatelier's principle [40] can be interpreted as: "for chemical reaction with increasing volume of products lower pressure will shift equilibrium towards reaction products". In other words, lower pressure is beneficial for nitrous oxide decomposition.
- It increases the thuster's nozzle throat to the size that is easy to manufacture.
- It improves thrust efficiency since flow friction losses in the thuster's nozzle throat are reduced.
- Higher nitrous oxide storage tank depletion can be achieved.
- Taking in account low mechanical (due to lower pressure) and moderate thermal (due to "slow" start-up) stresses exerted on thruster's casing it would be possible to use high temperature ceramic materials (such as, for example, alumina) for its design. Application of high temperature ceramics in thruster design will shift operating temperature and, thus, improve the specific impulse performance.

Slight increase in thruster size and mass due to lower operating pressure is not crucial for low-thrust propulsion system, and is a subject of optimisation.

Test Apparatus

As a first step towards the development of flight-qualified thruster the following simple test apparatus was designed. A 190mm-piece of 2.54mm-inner-diameter stainless steel pipe was adopted to house the catalysts. The test apparatus design is shown in Figure 4.

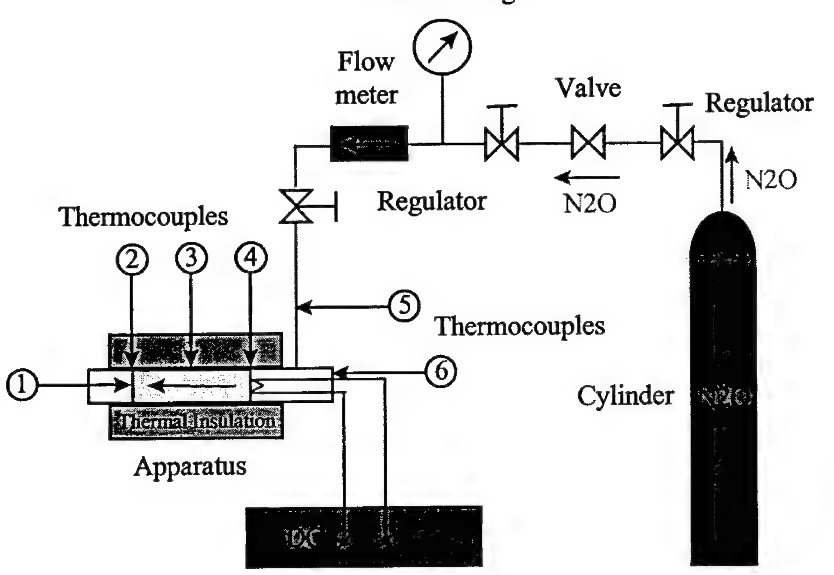


Figure 5. Test set-up schematics.

Experimental set-up for nitrous oxide decomposition research is shown in Figure 5. Nitrous oxide from the cylinder flows though the valve and regulators to the test apparatus where it decomposes on a catalyst before discharging to atmosphere. A pressure gauge and flow meter in the nitrous oxide feed line indicate flow parameters set by the regulators. Direct current power supply is necessary for heating a catalytic wire inside the apparatus. Thermal insulation is used to reduce heat loss from the decomposition chamber. Thermocouple *1* is set to read the temperature of exhaust gases. Thermocouples *2*, *3*, and *4* are set to measure decomposition chamber outside wall temperature. Thermocouple *5* is set in stream of nitrous oxide feed line. Thermocouple *6* measures the outside wall temperature of end plug of the apparatus.

Experimental Results

The potential for the nitrous oxide catalytic decomposition technique has been demonstrated in dozens of experimental tests at *Surrey Space Centre*, U.K. (see Figure 6). During these tests:

- The proof-of-concept was demonstrated.
- Repeatable, self-sustaining, decomposition of nitrous oxide has been achieved using different catalysts.
- Hot restarts at zero-power input have been repeatedly shown in operation.
- More than 50 different catalysts have been tested.
- A catalyst activation temperature as low as 250°C has been recorded.
- Nitrous oxide mass flow rates above 1.1gm/s have been supported.
- Decomposition temperatures in excess of 1500°C have been demonstrated.
- Electrical power input as low as 24W has been used.
- The time required to heat the catalyst from ambient to activation temperature has been as short as 3min.
- A catalyst lifetime in excess of 76min. was demonstrated.
- Nitrous oxide decomposition was shown to ignite solid fuel (PMMA). A vortex flow "pancake" hybrid rocket motor was successfully ignited by injection of hot gaseous products of the nitrous oxide decomposition into the combustion chamber (see Figure 7). [47] In the test, a well-known hydrazine decomposition catalyst (*Shell 405*) was used to decompose nitrous oxide.

Despite these achievements, two major challenges were revealed. Both of them are associated with choice of high temperature materials.

The first challenge is due to high temperature generated inside decomposition chamber. This temperature is enough to melt stainless steel casing (see Figure 8). Application of refractory materials in the design is presently not considered because they are difficult to manufacture and expensive. Lowering the process temperature is unfavourable because it sacrifices thruster performance. Application of alumina ceramics was found promising for high temperature casing design. However, additional tests comprising both thermal and mechanical stress loads need to be carried out before the final conclusion can be made. The future designs involving ceramics will require careful consideration of thermal expansion coefficients.

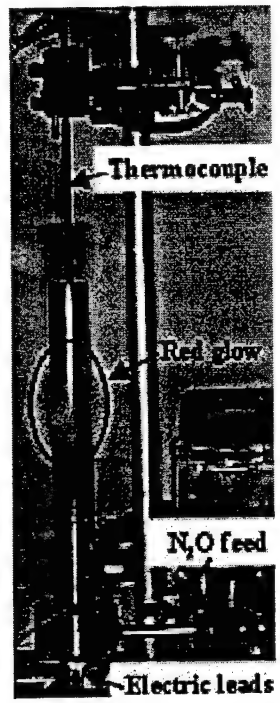


Figure 6. Self-sustaining nitrous oxide decomposition on *LCH 212* hydrazine catalyst. The electric leads have been disconnected from power supply after "ignition". No electric power is applied.

The second challenge is associated with high temperature (>1100°C) instability of the catalyst materials. The literature search on nitrous oxide decomposition catalysts provided no answer for the problem. Since practical applications for nitrous oxide decomposition catalysts are currently limited to environmental outlooks rather than power generation the maximum explored temperatures did not exceed 800°C. It is also believed that above this temperature homogeneous (or thermal) decomposition dominates the process. However, it was found that in the case of suggested dynamic system homogeneous decomposition rates at 800°C are not high enough to initiate self-sustaining decomposition; therefore, the need in high temperature catalyst still remains.

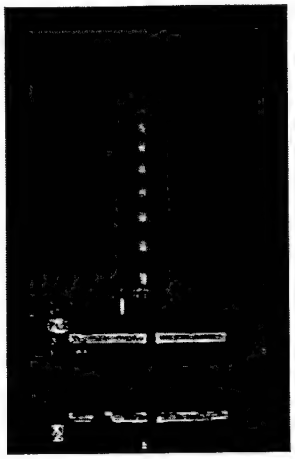
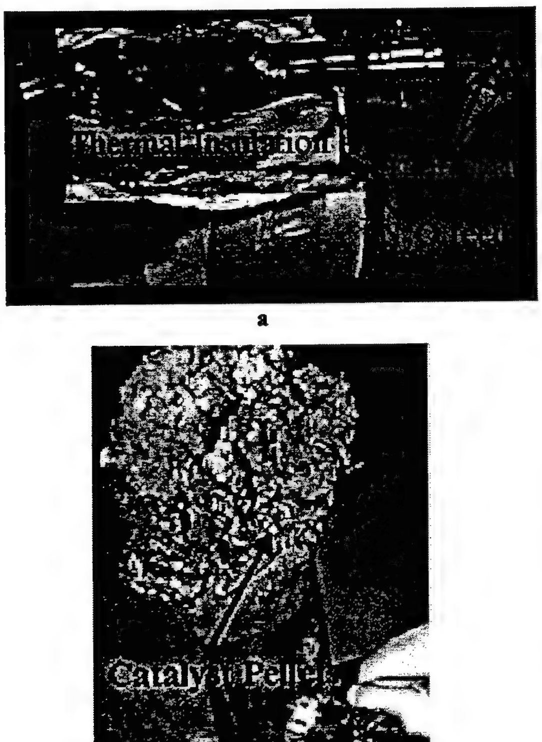


Figure 7. A vortex flow "pancake" hybrid rocket motor firing.



a

b

Figure 8. Test design after firing: a) Stainless steel pipe is melted with iron catalyst and *MICROPORE* thermal insulation; b) Alumina pellets coated by catalyst have survived the heat.

Meanwhile, it was found that above 1100°C the following problems occur:

- Zeolites and silica sinter
- Cordierite matrix does not withstand the temperature
- Iridium and rhodium oxides sublimate
- Nickel, cobalt and iron react with alumina or magnesia substrates forming spinels (complex oxides).

The work on high temperature stable catalysts continues.

Summary

Nitrous oxide has been identified at Surrey Space Centre as a rocket propellant for small satellites. Application of this propellant on small spacecraft is advantageous because:

- All propulsion functions for small satellites can be covered.
- Multi-mode propulsion system can be designed for a small satellite. Such a system will have lower total dry mass fraction and increase the number of mission scenarios due to more efficient propellant management.
- It has potential in providing significant reduction of propulsion system cost.

Previous research regarding nitrous oxide space application proved that:

- It can be stored in orbit.
- It can be used as a resistojet propellant.
- Its self-sustaining decomposition is attainable.

A continuation of earlier efforts, nitrous oxide catalytic decomposition is a focus of current research at Surrey. It is considered to be a key-technique for a novel monopropellant thruster concept. This technique reduces input power requirements for power-constrained small satellites in comparison with a thermal decomposition technique, and, therefore, will be affordable for smaller spacecraft. As a further step, nitrous oxide catalytic decomposition technique is suggested for bipropellant thruster ignition.

As a first approach towards the monopropellant thruster a catalytic decomposer for nitrous oxide has been designed and successfully tested along with supporting infrastructure.

Catalysts for nitrous oxide decomposition exist. They have been proven feasible for heat and thrust generation as well as hybrid rocket motor ignition.

Although the existing catalysts work well, high-temperature stable catalyst materials would further enhance the performance of a monopropellant thruster.

Current research at Surrey is focused on the investigation of the performance of a nitrous oxide catalytic decomposer leading towards the development of a nitrous oxide monopropellant thruster.

The ultimate research goal is to provide theoretical and experimental basis for the development of the first nitrous oxide multi-mode propulsion system for small satellite applications.

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NITROUS OXIDE AS A ROCKET PROPELLANT

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Abstract

Nitrous oxide is introduced as a multi-purpose propellant for spacecraft. Potential space applications of this propellant are given. Based on comparison to conventional systems, a multi-mode nitrous oxide propulsion concept is expected to deliver higher performance. Main features of a self-pressurising, nitrous oxide storage system are described. A nitrous oxide catalytic decomposition technique is suggested for restartable spacecraft propulsion. Up-to-date experimental results are presented. A conclusion describes the long-term feasibility of novel nitrous oxide propulsion option concepts.

1.0 Introduction

Nitrous oxide¶ (N_2O) offers many inherent advantages as a small satellite propellant. It is a colourless, non-toxic, liquefied gas with a slightly sweet taste and odour. It is non-corrosive and may be used with common structural materials. Nitrous oxide is stable and comparatively unreactive at ordinary temperatures, e.g. to ozone, hydrogen, the halogens, the alkali metals, etc. [1] It is decomposed into nitrogen and oxygen by heating above 520°C. [2] Chemical composition of the decomposition products ($36.3\%O_2 + 63.7\%N_2$) is akin to that of air. The decomposition reaction can be accelerated by a catalyst. At elevated temperatures nitrous oxide supports combustion and oxidises certain organic compounds, the alkali metals, etc. [1] Nitrous oxide is classified by the Department of Transportation as a non-flammable, compressed gas and is shipped with the required "Green Label". [1]
Three basic properties of nitrous oxide make it attractive as a multi-purpose rocket propellant:

- Can be stored as a liquid (~745kg/m^3) with a vapour pressure of ~52bar (at 20°C)
- Decomposes exothermically with adiabatic decomposition temperature reaching ~1640°C
- Free oxygen available by decomposition can be combusted with a wide variety of fuels

Taking advantage of these properties, especially the exothermic catalytic decomposition, space propulsion applications of nitrous oxide may be extended to:

- cold-gas propulsion for attitude control of a spacecraft
- monopropellant thruster for spacecraft station-keeping and small orbit manoeuvres
- bipropellant thrusters for large orbital manoeuvring
- power-generation on-board spacecraft or launch vehicle
- oxygen generation on board spacecraft

Since the whole range of propulsion functions can be covered by one self-pressurising propellant, multi-mode propulsion systems can be envisioned to satisfy a wide variety mission requirements. Such systems would employ different types of thrusters fed by nitrous oxide from a single, simply designed storage tank.
Nitrous oxide is not new to the propulsion community. Previously, the American Rocket Company (*AMROC*) used nitrous oxide as an oxidiser for its hybrid rocket motors. [3] However, it has yet to be officially recognised as a rocket propellant, nitrous oxide is also used in amateur rocketry in combination with solid

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¶ also known as "laughing gas", dinitrogen oxide, or dinitrogen monoxide

(polypropylene, hydroxyl-terminated polybutadiene (HTPB), asphalt, etc.) and liquid (alcohols, etc.) fuels. [4-8] Surrey Space Centre's *Mark-IV* resistojet thruster uses this gas for orbit correction on the *UoSAT-12* mini-satellite. [9-11] The *Space Cruiser System,* a fully recoverable and reusable piloted passenger carrying sub-orbital space-plane, is planned to use three nitrous oxide/propane pressure fed, rocket engines. [12,13]

This paper introduces nitrous oxide as a multi-purpose propellant for spacecraft. The advantage of employing this propellant on small spacecraft is shown in the following performance comparison of different thruster types.

2.0 Performance Comparison

The arguments in favour of nitrous oxide for space applications are discussed below by comparison to conventional and alternative propellants.

2.1 Cold-gas

Cold-gas propulsion is typically used for attitude control of the spacecraft because of the ability of such a system to provide a small minimum impulse bit. Ten common, easily available gases were selected for comparison. The results of the comparison are presented in Figure 1. The gas storage conditions along with other properties for comparison are given in Table 1.

Although nitrous oxide (along with carbon dioxide) provides the lowest theoretical specific impulse it has the second highest storage density amongst the selected cold-gas propellants. Therefore, it is able to deliver a higher change in total spacecraft velocity per unit volume of propellant (i.e. density Isp) compared with butane, propane, ethylene, methane, nitrogen, helium and hydrogen, all of which provide higher specific impulses but lower densities. Denser propellants are preferable for small satellites, which are volumetrically constrained by launch requirements as secondary payloads. Nitrous oxide has the third highest density Isp after ammonia and carbon dioxide.

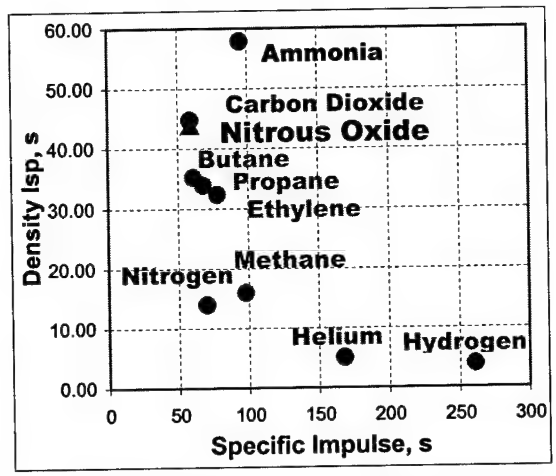


Figure 1 Theoretical performance comparison of cold-gas propellants. (nozzle expansion ratio = 200)

TABLE 1: *Properties of selected cold-gas propellants.*

Name	Chemical Formula	Storage Conditions			Toxicity	Flammability	Remarks
		State	Density kg/m^3	Pressure bar			
Ammonia	NH_3	liquid	609	8.9	T	N	highly reactive
Butane	C_4H_{10}	liquid	578	2.2	N	F	non-corrosive
Carbon Dioxide	CO_2	liquid	758	58.9	N	N	not chemically active
Ethylene	C_2H_4	gas	415	202.7	N	F	non-corrosive
Helium	He	gas	30	202.7	N	N	inert
Hydrogen	H_2	gas	15	202.7	N	F	non-corrosive
Methane	CH_4	gas	163	202.7	N	F	non-corrosive
Nitrogen	N_2	gas	220	202.7	N	N	inert
Nitrous Oxide	N_2O	liquid	745	52.4	N	N	supports combustion
Propane	C_3H_8	liquid	499	8.6	N	F	non-corrosive

Notes: Storage conditions are taken at 21°C. T – toxic; F – flammable; N – non-toxic or non-flammable.

TABLE 2: *Properties of selected monopropellants.*

Propellant	Nitrous Oxide	Hydrogen Peroxide	Hydrazine
Chemical Formula	N_2O	H_2O_2	N_2H_4
Specific Impulse (theoretical), s	206	179	245
Storability	Storable	Storable (decomposes)	Storable
Storage Density, kg/m^3	745 @ 21°C 52.4 bar	1347	1004
Vapour pressure	50.8bar @ 20°C	0.00345bar @ 20°C	0.0214bar @ 26.7°C
Storage Temperature Range, °C	-34—60	-7—38	9—40
Toxicity	Non-toxic	Burns skin	Very Toxic
Flammability	Non-flammable	Non-flammable	Flammable
Flight Heritage	feed system UoSAT-12	flown	flown

Notes: All propellants are stored in liquid state. Hydrogen peroxide is 89% strength. Theoretical specific impulse data obtained for nozzle expansion ratio of 200.

Ammonia, however, is a toxic, highly reactive chemical that in combination with air may present an explosion hazard. Ammonia is incompatible with copper, tin, zinc and their alloys. Due to its high triple point, carbon dioxide may solidify in the feed lines and requires a thermal control system. Conversely, nitrous oxide is non-toxic, non-flammable; it has a low triple point and is compatible with common structural materials.

2.2 Monopropellants

Three monopropellant propulsion technologies have been selected for this comparison. Nitrous oxide monopropellant thruster performance is compared with that of hydrogen peroxide and conventional hydrazine thrusters for micro-satellite applications. (see Table 2)

The comparison reveals that a nitrous oxide monopropellant thruster is capable of moderate theoretical specific impulse performance, 16% lower than that of for hydrazine but 15% higher than that of for hydrogen peroxide thrusters.

Each of these propellants can be stored on board the spacecraft. Although storage density of liquefied nitrous oxide is 26% lower than that of hydrazine and 45% lower than that of hydrogen peroxide, low vapour pressure of these two propellants requires the use of a separate expulsion system.

The storage temperature range of nitrous oxide varies as a function of vapour pressure, tank design pressure and ullage volume. It is discussed in detail later in this paper. In general, this range is broader than that of hydrogen peroxide and hydrazine. Storage temperature ranges for hydrogen peroxide vary as a function of its concentration. For the case of 89% strength hydrogen peroxide the low temperature limit is defined by a freezing point of -12°C. Five-degree margin between low operational limit and freezing point is a precaution against formation of slush. A similar estimate is applied to hydrazine that has freezing point of about 2° C. Although the boiling temperature of hydrogen peroxide is 141°C, the strong temperature dependence of its decomposition rate limits the storage temperature to below 38°C. [14] For hydrazine the upper storage temperature is limited to 40°C although the boiling point is 113°C.

In addition to raw performance, propellant handling is another significant issue to consider. Nitrous oxide handling requires minimal safety equipment, while splash protection is necessary for hydrogen peroxide. Complete protection is essential for hydrazine handling. [15] Nitrous oxide presents no fire or explosion hazard, while hydrogen peroxide may spontaneously ignite on contact with hydrocarbons. Contaminated hydrogen peroxide is unstable and presents a serious explosion hazard. High fire and explosion hazards are associated with hydrazine.

Although a nitrous oxide monopropellant thruster has yet to be flown, the feed system for a rersistojet is currently under orbital test on-board the *UoSAT-12* mini-satellite. Hydrogen peroxide monopropellant thrusters were employed on the number of missions. [16—18] Presently, hydrazine monopropellant thrusters are an extensively used space technology. [19,20]

2.3 Resistojets

Heating a propellant in a resistojet improves specific impulse performance in comparison with cold-gas thrusters. Due to low heat transfer rates, resistojets are preferable for long duration firings. Therefore, orbit maintenance (or station-keeping) is a suitable function for such a thruster. Since power is the major constraint for electric thrusters on small spacecraft, specific impulse of several resistojet propellants is compared (in Figure 2) by consumed energy. From that perspective, an *"ideal"* resistojet propellant for a small spacecraft would deliver the highest specific impulse at

minimum input power. Therefore, it would locate itself towards top left corner of the figure. In this figure, a curve for more efficient propellant would be steeper then that of for a less efficient one. Ordinate axis of the graph corresponds to zero-power operational modes. Two of such modes are possible, when a resistojet is run as a cold-gas system, and when the heat generated as a result of initiated self-sustaining exothermic decomposition reaction is used. This latter feature can be described as a monopropellant mode.

From this figure, hydrogen is a good propellant because its basic high specific impulse grows fast with only little additional heating. However, its low density violates volumetric constraints for small satellite discussed earlier. The next best option would appear to be hydrazine.

Nitrous oxide resistojet is a special case. From the start, its performance almost overlaps that of nitrogen resistojet until self-sustaining decomposition is initiated. At that point, power input can be turned off, and the thruster will continue to operate as a monopropellant. Since the maximum temperature of nitrous oxide decomposition (~1640°C) is high, heating of its reaction products in resistojet is impractical due to the challenging choice of high temperature construction materials. Thus, the practical temperature operating range for nitrous oxide resistojet coincides with that of a monopropellant described above. The power savings associated with nitrous oxide catalytic decomposition in a monopropellant, however, support its use instead of resistojet.

On the whole, the specific impulse that can be delivered by hydrazine resistojet is higher than that of nitrous oxide resistojet or monopropellant. However, hydrazine toxicity and higher powers (>100W) required for such a resistojet might become prohibitive drawbacks for small satellite applications. In this case, the non-toxic nitrous oxide resistojet or monopropellant operating at zero-power mode are desirable.

Work on low-power resistojets was started at Surrey by Timothy Lawrence in 1995.[9-11] Since then:

- The highest recorded specific impulse of the *Mark-III* nitrous oxide resistojet was 148s.
- During vacuum test of the *Mark-III* resistojet at the US Air Force Research Lab at *EDWARDS* Air Force Base, CA, nitrous oxide self-sustaining decomposition was observed for longer than 18 hours.
- The first (0.1N and 100W) nitrous oxide resistojet thruster *Mark-IV* has been successfully commissioned on board the *UoSAT-12* mini-satellite (see Figure 3).

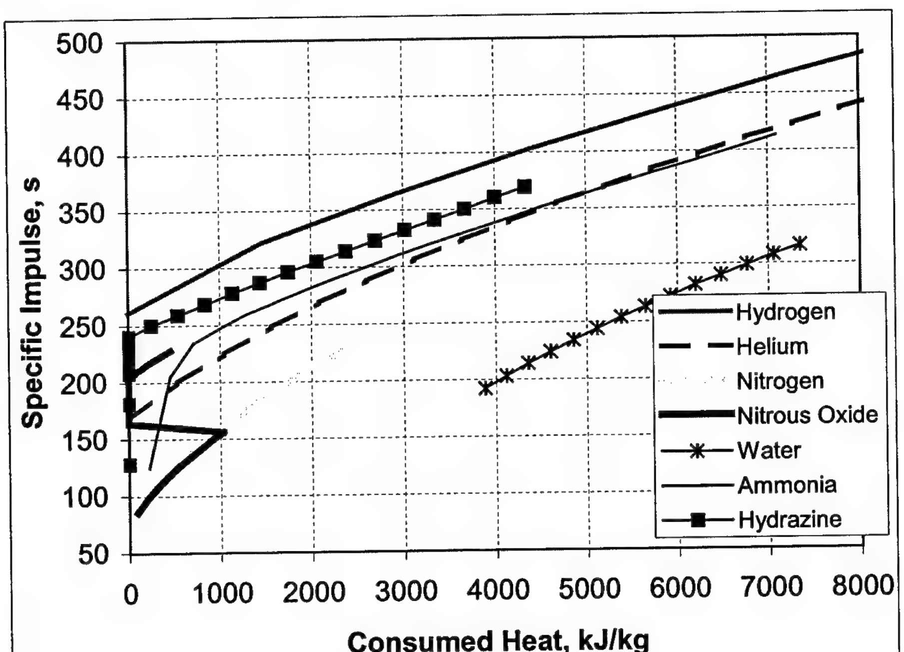


Figure 2 Theoretical performance comparison of resistojet propellants: specific impulse vs. heat required for heating propellant to the process temperature.

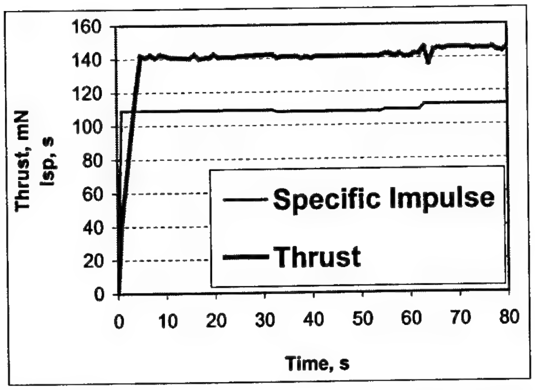


Figure 3 Thrust and specific impulse for *UoSAT-12* resistojet firing on 11April 2000.

2.4 Bipropellants

Generated by nitrous oxide decomposition, a hot nitrogen-oxygen mixture can be exhausted through a nozzle as a monopropellant or used to combust a fuel. The amount of free oxygen liberated in nitrous oxide decomposition is comparable to hydrogen peroxide, and pure gaseous oxygen (GOX) at 152 bar of storage pressure (see Figure 4). Although GOX has maximum mass fraction, available oxygen mass content bound in nitrous oxide and hydrogen peroxide is higher per unit of volume.

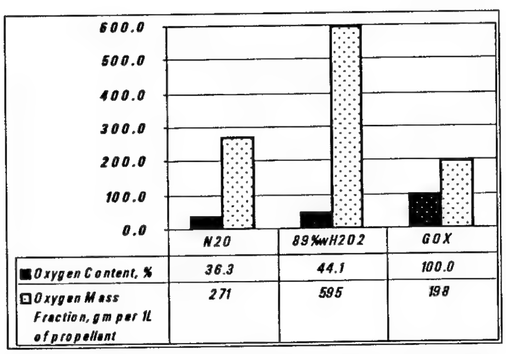


Figure 4 Amount of free oxygen available for combustion.

A hot nitrogen-oxygen mixture generated by nitrous oxide decomposition can be used to combust a fuel. Therefore, bipropellant thrusters employing nitrous oxide as an oxidiser are feasible.

Theoretical performance of several nitrous oxide bipropellant combinations has been evaluated to determine their feasibility for future applications. HTPB, PE and RP-1 are identified as three the most practical fuels for nitrous oxide bipropellants on small satellites and upper-stages. [15]

In Figure 5, the performance of these three is compared to conventional propellant combinations. Although the theoretical performance of the non-toxic bipropellants is somewhat lower than that of highly toxic conventional nitrogen tetroxide/hydrazine family propellant combinations it is still high enough (330s) to be considered for small satellite applications. [19, 20]

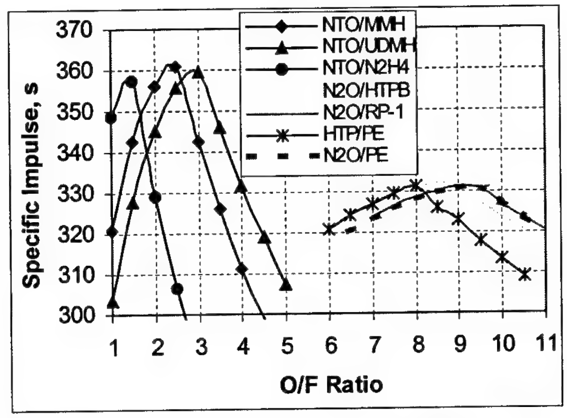


Figure 5 Theoretical performance of bipropellant combinations using nitrous oxide as an oxidiser. **

2.5 Multi-Mode Propulsion System

For flexible small satellite missions, multi-mode propulsion systems are essential. Multi-mode propulsion systems are designed to offer a range of thrust and total spacecraft velocity change options to meet specific mission objectives, e.g. orbit insertion, station-keeping, and attitude control. While the use of nitrous oxide as a propellant may not be compelling when viewed in isolation for specific applications, its advantages over other propellant options in multi-mode systems become far more apparent. This is best illustrated by looking at a specific example that lends itself to an "apples-to-apples" comparison.

** The performance is calculated by USAF ISP computer code.

HTPB – Hydroxyl-Terminated Polybutadiene
HTP – High Test Hydrogen Peroxide (here 89%w/w)
MMH – MonoMethyl Hydrazine
N2H4 – Hydrazine
N2O – Nitrous Oxide
NTO – Nitrogen Tetroxide
PE – Polyethylene
RP – Rocket Propellant (kerosene)
UDMH – Unsymmetrical DiMethyl Hydrazine

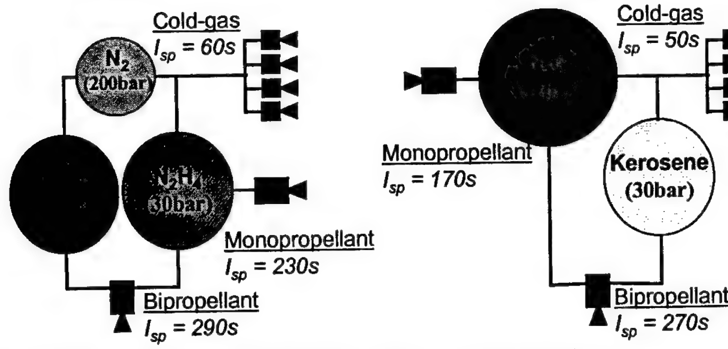
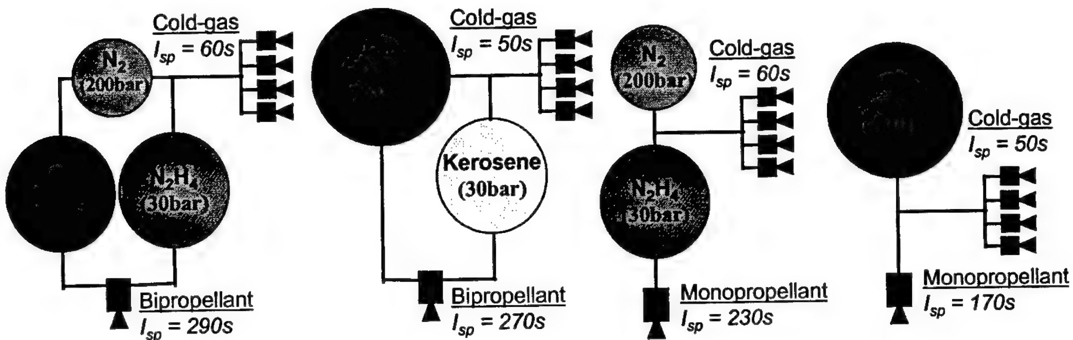


Figure 6 Schematics of triple-mode propulsion system options for a small satellite.



a **b**

Figure 7 Schematics of dual-mode propulsion system options for small satellite: a) Col-Gas/Bipropellant; b) Cold-Gas/ Monopropellant.

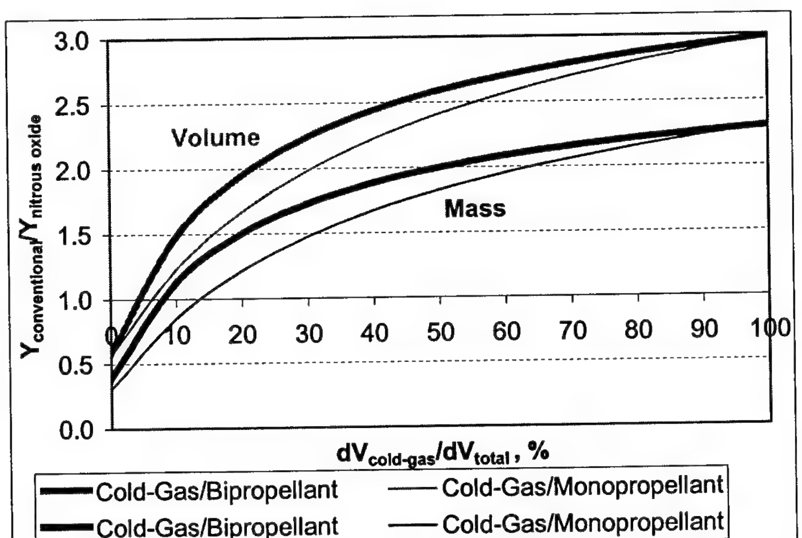


Figure 8 Performance comparison of conventional vs. nitrous oxide propulsion. (**dV** – spacecraft velocity change; **Y** – denotes propulsion mass or volume respectively)

Triple-mode propulsion system (Figure 6) is taken out of a variety of possible multi-mode systems as an example. The propulsion system's mass and volume were analysed with respect to contribution of each mode to total spacecraft velocity change. The dual-modes in Figure 7 represent the extreme cases of triple-mode system analysis when contribution to total spacecraft velocity change by bi- or monopropellant mode vanishes. The triple-mode performance falls in between the performance of these dual-mode systems. The results of comparison are summarised in Figure 8. In this Figure abscissa axis shows contribution of cold-gas mode fraction to total spacecraft velocity change. Ordinate axis gives a ratio of total volume or mass of conventional to nitrous oxide propulsion system. When this ratio is equal to one the performance of conventional and nitrous oxide propulsion is the same. Below 1.0, the performance on conventional propulsion is better than that of nitrous oxide system. Above 1.0, the performance of nitrous oxide is superior over that of conventional system.
The graph shows that:

- For the most of the range total volume and mass of triple-mode propulsion using nitrous oxide is lower than that of an alternative conventional system.
- Both parameters improve with increasing cold-gas propulsion fraction.
- Application of nitrous oxide propulsion is more advantageous over conventional system in the case of cold-gas/bipropellant mode.

Therefore, the application of nitrous oxide triple-mode propulsion system is beneficial for cold-gas fraction at which its total volume and mass is lower than that of an alternative conventional system.
The particular numbers can be read on the graph. Although these numbers are the attributes of the particular design and, thus, may change drastically the tendency will still remain.
On the whole, the non-toxic nitrous oxide system is of simpler design than that of using toxic hydrazine propellant.
In the case of the nitrous oxide system, the propellant may be used till depletion by either mode with no restrictions except a provision required for total spacecraft velocity change. Meanwhile, in the case of hydrazine, margins for use of the propellants by each mode must be imposed. Hence, application of nitrous oxide system would give an important advantage of the flexibility in firing strategy during mission. Therefore, since the propulsion requirements are more relaxed for nitrous oxide systems a number of considered in orbit mission scenarios can be increased. This feature is important especially for a spacecraft launched as a secondary payload since launch itself is often undefined until a few months to the launch date.

2.6 Conclusion

While not delivering the best specific impulse performance as a single-mode, nitrous oxide as a multi-mode, self-pressurising propulsion system simplifies the design and may provide higher total spacecraft velocity change and/or reduce mass. In addition, a nitrous oxide multi-mode system will benefit from non-toxicity, non-flammability and compatibility of the propellant in comparison to conventional hydrazine propulsion. Propulsion packaging and integration of such a system into spacecraft are easier. Flexibility of the firing strategy gained with a nitrous oxide multi-mode system increases the number of mission scenarios as well as launch opportunities.

3.0 Approach

Two main propulsion features must be considered for practical applications on board the spacecraft. The system should be able to store propellant on board the spacecraft for a long duration missions (i.e. years), and it must be restartable in orbit. The technical issues associated with nitrous oxide storage and propulsion restarts are discussed below.

3.1 Storage System

Nitrous oxide is a storable propellant that does not require an expulsion system. When dispensed in a pressurised tank, it exists in two forms, liquid and gas. At room temperature the pressure of a full tank, regardless of size, will read approximately 52bar. Since nitrous oxide is a liquefied gas, the pressure will remain constant as long as any liquid remains in the tank. When the tank has been used to the point where a liquid phase no longer exists (after approximately 75% to 80% consumption), then the pressure will start to drop.
Above its critical temperature 36.5°C nitrous oxide will convert completely to a gas and the discharge of the tank content will show a steady drop in pressure. [1]
Pressure of gaseous nitrous oxide can be calculated by Benedict-Webb-Rubin (BWR) equation of state within temperature range from -30°C to 150°C, for densities up to 900kg/m^3, and maximum pressure of 200bar. [21]
This equation is used to predict nitrous oxide pressure variation inside a storage tank as a function of temperature (see Figure 9 and 10).

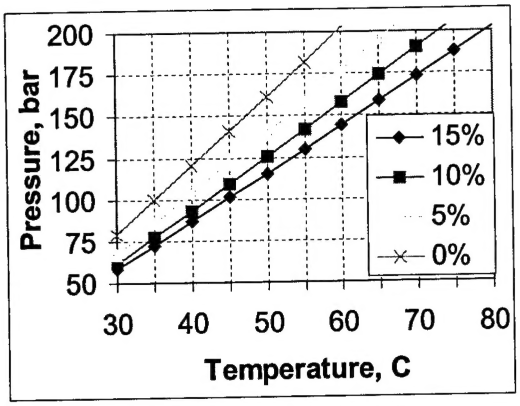


Figure 9 Storage pressure of nitrous oxide tank as a function of temperature and ullage volume (0, 5 10, 15%).

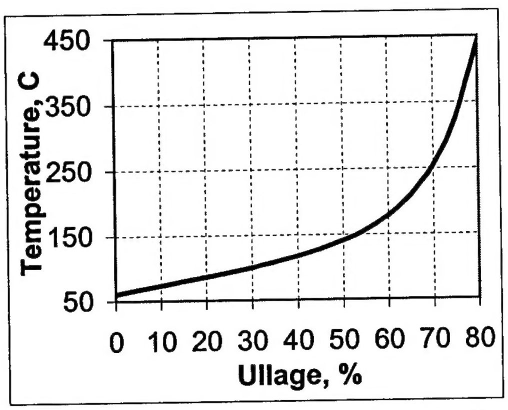


Figure 10 Allowable storage temperature of nitrous oxide tank as a function of ullage volume (at 200bar).

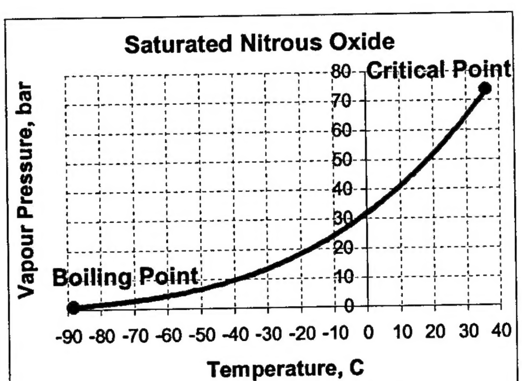


Figure 11 Nitrous oxide vapour pressure as a function of temperature.

On the other hand, chilling the tank lowers the pressure (and thus nitrous oxide flow rate) dramatically (as shown in Figure 11).

In general, nitrous oxide can be stored as liquid or compressed gas (above the critical point) through the wide temperature range limited perhaps by thermal decomposition temperature of 520°C on the upper end and the triple point on the lower end of the scale. [1,2]

The maximum storage temperature limit is dependant on provisioned tank pressure and ullage volume. The practical maximum operational temperature number for designed tank pressure of 200bar would be 60°C. However, it increases while the propellant is consumed. The recommended low operational temperature is -34° C. This would allow tank operational pressure (i.e. nitrous oxide vapour pressure) stay above 11bar.

In bipropellant propulsion nitrous oxide vapour pressure may be used for pressurisation of liquid fuel. In this case two principal designs are possible: a) oxidiser and fuel are stored in separate but connected tanks; b) single storage tank is used for both propellant components (see Figure 12). Although at normal temperature combination of fuels with nitrous oxide is non-hypergolic, complete seal between the propellants must be insured to avoid their mixing – a cause of a potential explosion hazard.

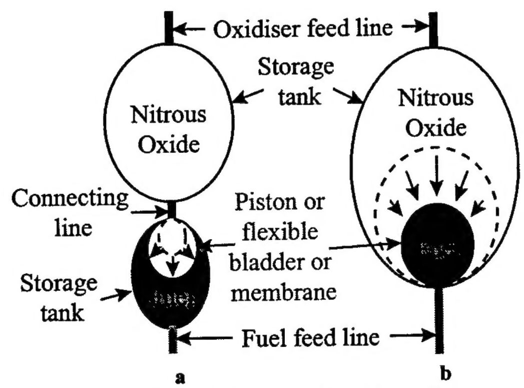


Figure 12 Schematics of self-pressurising bipropellant system designs: a) separate tanks; b) single tank.

Recent experience of storing nitrous oxide on-board the *UoSAT-12* mini-satellite for more than one year indicates that storage of the gas in-orbit is not a problem.

3.2 Start-up

Restartability is an essential feature for spacecraft propulsion when more than one in-orbit manoeuvre is required. Therefore, repeatable start-up is necessary

for propulsion in orbit. Start-up in vacuum and in the micro-gravity environment is not a trivial task.
Catalytic decomposition is one possible in-orbit start-up technique for nitrous oxide propulsion that is suggested for mono- and bipropellant thrusters. [15, 22] This start-up leads to significant power savings over thermal decomposition techniques employed in a resistojet. This will make nitrous oxide propulsion a feasible option expending its application range from mini-satellite (100-500kg) to micro-satellite (10-100kg) platforms.

4.0 Experimental Results

The potential for nitrous oxide catalytic decomposition technique has been demonstrated in dozens of experimental tests at Westcott test facility of *Surrey Space Centre* (U.K.). During these tests:

- The proof-of-concept was demonstrated.
- Repeatable, self-sustaining, decomposition of nitrous oxide has been achieved using different catalysts.
- Hot restarts at zero-power input have been repeatedly shown in operation.
- More than 50 different catalysts have been tested.
- A catalyst activation temperature as low as 250°C has been recorded.
- Nitrous oxide mass flow rates above 1.1gm/s have been supported.
- Decomposition temperatures in excess of 1500°C have been demonstrated.
- Electrical power input as low as 24W has been used.
- The time required to heat the catalyst from ambient to activation temperature has been as short as 3min.
- A catalyst lifetime in excess of 4 hours was demonstrated.
- Catalytic decomposition technique has been proven to ignite solid fuel (plexiglass[±]). Vortex flow pancake hybrid rocket motor was successfully lit up by injection of hot gaseous products of nitrous oxide decomposition into combustion chamber. In the test well-known hydrazine decomposition catalyst (*Shell 405*) was used to decompose nitrous oxide.

Despite the achievements the problems associated with high temperature (>1100°C) instability of catalyst materials still remain. [22] Although the existing catalysts work well for suggested applications, high-temperature stable catalyst materials would enhance the performance of a monopropellant thruster.
Current research at Surrey is focused on development of nitrous oxide monopropellant thrusters and high-temperature decomposition catalysts.

5.0 Summary

Nitrous oxide is a promising propellant for future low cost, small satellite missions. The research regarding application of this gas as a rocket propellant for small satellites is currently under way at Surrey Space Centre.
The experience obtained shows that:

- It can be stored in orbit.
- It can be decomposed on a catalyst.
- The decomposition generates heat and thrust.
- Self-sustaining nitrous oxide decomposition is achievable.
- Generated hot exhaust can ignite fuel upon contact.

Therefore, nitrous oxide cold-gas, monopropellant, resistojet, and bipropellant thrusters are feasible.
The results of performance comparison of these systems show that application of nitrous oxide:

- Dense, liquefied gas for cold-gas propulsion is beneficial on volume-constrained small satellites.
- Resistojet or monopropellant is beneficial on power-constrained small satellites.
- Monopropellant and bipropellant will reduce major "safety overheads".
- Multi-mode systems will be more effective over conventional single-mode alternatives.

The following advantages of nitrous oxide multi-mode propulsion offer:

- Higher total spacecraft velocity change performance over conventional single-mode alternatives.
- Propulsion power budget reduction.
- Design simplicity.
- Ease of packaging and integration on spacecraft.
- Firing strategy flexibility.
- Increased number of mission scenarios and launch opportunities.
- Reduction in propulsion system cost.

In addition, power and oxygen-rich atmosphere can be generated on board the spacecraft by nitrous oxide decomposition.
To develop nitrous oxide multi-mode propulsion further research is required in:

- Catalytic decomposition for monopropellant thruster application.
- Combustion for bipropellant thrusters application.

± Poly-Methyl Methacrylate (PMMA)

- High-temperature stable catalyst materials.

The research will lead to the development of low cost propulsion system for small satellites.

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